Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

REPORT, GENERAL

NEAR SURFACE DISPOSAL FACILITY REFERENCE INVENTORY REPORT

NEAR SURFACE DISPOSAL FACILITY (NSDF)

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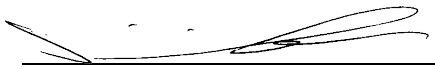
Revision 3

Prepared by:		2020/04/01
	Jérôme Besner Program Officer, Waste Program	Date
Reviewed by:		2020/04/01
	Michael Labriola Safety & Licensing Analyst, NSDF Regulatory Approvals	Date
Approved by:		2020/04/01
	Meggan Vickerd Director, NSDF Projects	Date
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REVISION HISTORY

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3	2020/04/01	Issued as “Approved for Use”. Revised to address CNSC comments	J. Besner	M. Labriola	M. Vickerd
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TABLE OF CONTENTS

SECTION **PAGE**

FIGURES

TABLES

1. INTRODUCTION

Canadian Nuclear Laboratories, (CNL) is undertaking the design, licensing and construction of a Near Surface Disposal Facility (NSDF) at the Chalk River Laboratories (CRL) site. The Facility is being designed to accept and permanently dispose of legacy low-level waste from decades of nuclear operations, future environmental remediation and decommissioning efforts across the range of Atomic Energy of Canada Limited (AECL) sites, as well as wastes generated by site operations in the future.

Waste packages currently stored in CNL Waste Management Area(s) (WMAs) and projections from facility decommissioning and environmental remediation projects, are inputs to developing the reference inventory for the NSDF. The primary source of waste generation is the CRL site, with additional waste from other AECL sites and small Canadian generators, such as hospitals and universities.

The proposed inventories were developed in three logical steps:

1. Assemble characterization data obtained or derived from waste package records, facility decommissioning and environmental remediation projects.
2. Assess the data against the Waste Acceptance Criteria (WAC) and report total radioactivity and radionuclide concentrations.
3. Evaluating the reported inventory against the safety criteria to confirm it is acceptable for the post-closure safety assessment (not in scope of this document).

The proposed inventories for the NSDF have evolved with the project based on various input, as they have become available; including the development of the NSDF WAC, public feedback from the review of the draft Environment Impact Statement, and post-closure safety assessment modelling. Figure 1 provides a graphic representation of the iterative process that led to the development of the current NSDF Reference Inventory.

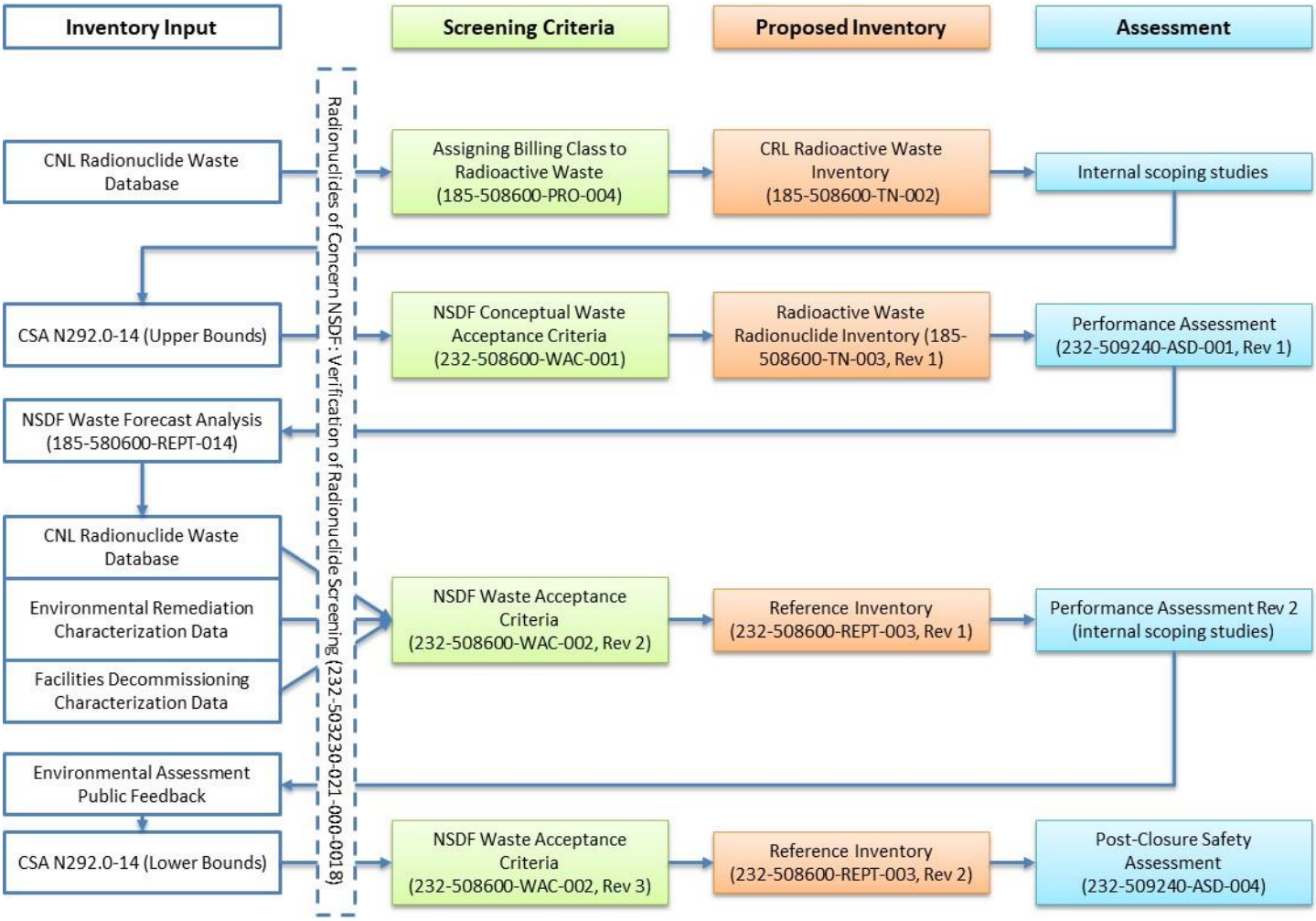

Figure 1 Reference Inventory Development Iterative Process
[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], and [13]

2. PURPOSE AND SCOPE

The NSDF Reference Inventory establishes a representative radionuclide inventory by extrapolating existing waste packages, environmental remediation projects and decommissioning projects data to an assumed total volume of the NSDF at time of closure (i.e., end of operations phase in ~2070).

The purpose of this document is to provide an estimation of the total radiological inventory required to inform the safety assessments where the inventory is tested against selected scenarios to determine the long-term consequences of the proposed facility.

Notably, the NSDF Reference Inventory informs NSDF Design Documents [14], the Waste Characterization Report [15], Post-Closure Safety Assessment [13], Environmental Impact Statement [16] and the Safety Analysis Report [17].

The NSDF Reference Inventory does not qualify any specific materials for disposal; all waste will be evaluated against all requirements of the licensed NSDF.

3. INPUTS TO THE NSDF REFERENCE INVENTORY

The following information was used to prepare the NSDF Reference Inventory:

- Knowledge of the waste generating processes;
    - Data from historical waste packages in storage;
    - Estimates of materials and their radioactivity developed by decommissioning projects in the planning phase for structures to be demolished;
    - Estimates of materials and their radioactivity from environmental remediation projects in the planning phase for affected lands to be remediated;
- Identification of radionuclides that contribute to safety criteria;
- Waste Volume Distribution; and
- Limits on radioactivity concentrations for the NSDF.

3.1 Knowledge of the Waste Generating Processes

Wastes across the CNL sites represent approximately 70 years of operations from waste generating processes; predominantly operation of nuclear research reactors, fuel research facilities, laboratory activities, and isotope production facilities. The radioactive wastes proposed for the NSDF exists mainly in the form of contamination deposited on facility surfaces and equipment, and on tools, protective clothing and labware. As well, the radioactive waste includes activated materials and Technologically Enhanced Naturally Occurring Radioactive Materials. Fission products, activation products, fissionable material and actinides exist in the radionuclide distribution of CNL waste streams. Safeguarded material is expected to have been managed by site administrative processes upstream of waste generation and not present in the wastes proposed for the NSDF.

The radioactivity of waste packages generated by these processes is provided by the records in CNL's radioactive waste database and in project projections for decommissioning and environmental remediation projects. This is further explored in Section 4.

3.2 Radionuclide Screening

There are hundreds of radionuclides that can be present in radioactive waste. For example, the Chalk River Radioactive Waste Database has had over 200 radionuclides recorded during the last 25 years (see Table A-1 in Appendix A). Many of these radionuclides are present at low activities, or have very short half-lives, such that they cannot contribute significantly to the radiological impact. As well, many of the radionuclides are short-lived in-growth products, such as Ba-137m, which considered in the analysis in conjunction with their respective parents (e.g. Cs-137).

During the initial screening of radionuclides, radionuclides with half-lives less than 5 years and noble gases were removed. The activities of the remaining radionuclides present in the waste database were then extracted and are found in Table A-2.

A set of 30 radionuclides was used for the NSDF Reference Inventory as presented in Table 1. To demonstrate that these radionuclides considered in the analysis are the primary radionuclides contributing to the dose consequence, the following approach was used:

1. Evaluate radionuclides significance:
    - Define dominant pathways.
    - Consider full radionuclide dataset available in CRL' Waste Inventory Program (WIP-III).
    - Rank radionuclides, taking into account activities and dose coefficients corresponding to significant pathways.
    - Consider other factors, such as the effect of decay and in-growth and sorption properties.
2. Compare against similar studies.
3. Determine if the list used in NSDF studies and design is fit for purpose.

Further information on this process is available in Appendix B.

Table 1
Radionuclides used for the NSDF Reference Inventory

Radionuclide	Element Name	Half Life [18]	Predominate Decay Emissions [18]
Ag-108m	Silver	438 years	gamma
Am-241	Americium	432.6 years	alpha/gamma
Am-243	Americium	7 364 years	alpha
C-14	Carbon	5 700 years	beta
Cl-36	Chlorine	3.013E+05 years	beta
Co-60	Cobalt	1 925.28 days	beta/gamma
Cs-135	Cesium	2.3E+06 years	beta
Cs-137	Cesium	30.08 years	beta/gamma
H-3	Hydrogen	12.32 years	beta
I-129	Iodine	1.57E+07 years	beta/gamma/x-ray
Mo-93	Molybdenum	4.0E+03 years	x-ray
Nb-94	Niobium	2.03E+04 years	beta/gamma
Ni-59	Nickel	7.6E+04 years	x-ray
Ni-63	Nickel	101.2 years	beta
Np-237	Neptunium	2.144E+06 years	alpha/gamma
Pu-239	Plutonium	24 110 years	alpha
Pu-240[(a)]	Plutonium	6 561 years	alpha
Pu-241	Plutonium	14.329 years	beta
Pu-242	Plutonium	3.75E+05 years	alpha
Ra-226	Radium	1 600 years	alpha/gamma
Se-79	Selenium	3.27E+05 years	beta
Sn-126	Tin	2.30E+05 years	beta/gamma
Sr-90	Strontium	28.79 years	beta
Tc-99	Technetium	2.111E+05 years	beta
Th-230	Thorium	7.54E+04 years	alpha
Th-232	Thorium	1.40E+10 years	alpha
U-233	Uranium	1.592E+05 years	alpha

Radionuclide	Element Name	Half Life [18]	Predominate Decay Emissions [18]
U-234	Uranium	2.455E+05 years	alpha
U-235	Uranium	7.04E+08 years	alpha/gamma
U-238	Uranium	4.468E+09 years	alpha/gamma
Zr-93	Zirconium	1.61E+06 years	Beta

Note a: Activities of Pu-240 are reported combined with Pu-239.

3.3 Waste Volume Distribution

Data describing the radioactivity of stored packages, data from scoping surveys and sampling for some of the structures on the CRL site and data from investigations of affected land areas at CRL was used in the preparation of NSDF Reference Inventory. Table 2 provides the projected volume by material for the NSDF and Figure 2 provides a graphic representation of the projected volume by material for the NSDF.

Table 2
Projected NSDF Waste Volumes, by Waste Type

Waste Type	Initial Volume Distribution Estimate (m^3) [8][(a)]	Additional Waste Added (m^3)	Volume Distribution Used for the Reference Inventory (m^3)	Volume after Linear Extrapolation to 1 000 000 m^3 (m^3)
Type 1: Soil and Soil-Like	363 451	60 500[(b)]	423 951	472 432
Type 2: Co-mingled	60 967		60 967	67 939
Type 3: Non Soil-Like	170		170	189
Type 4: Decommissioning & Demolition	282 791		282 791	315 130
Type 5: Packaged	119 753	260[(c)]	120 013	133 737
Type 6: Oversized Debris	9 488		9 488	10 573
Total	**836 620**	**60 760**	**897 380**	**1 000 000**

Note a: The Waste Forecast Analysis [8] includes the assumption that the NSDF would be able to accept some Intermediate-Level Radioactive Waste (ILW). The Reference Inventory does not include ILW, however kept the ratios of waste types from the Waste Forecast and performed a linear extrapolation of the Type 5 waste to make up the approximately 2 000 m3 that the ILW originally represented.

Note b: This volume represents the compacted waste volume from soil stored in WMA F [19].

Note c: This volume represents solidified stored liquid waste, which was being explored for disposal in NSDF when the Reference Inventory was being developed.

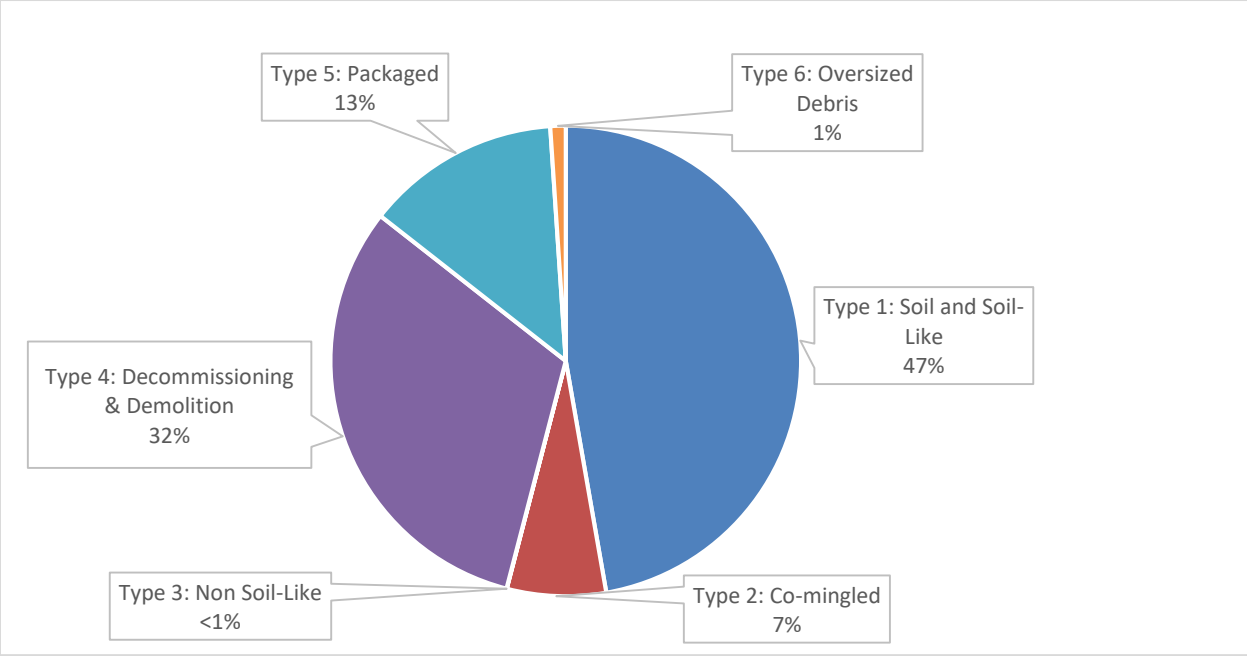

Figure 2 Projected Volume Distribution for the NSDF by Waste Type

For the Reference Inventory, specific characterization information was not available for all the waste types, therefore, the waste types were grouped based on primary source of generation as presented in Table 3.

Table 3
Projected NSDF Waste Volumes by Waste Type

	Raw Volume (no compaction, no fill or cover) (m^3)	**Projected Raw Mass (no fill or cover) (kg)**	**Source of Mass**
Environmental Remediation Wastes (Type 1-3)	541 000	8.10E+08	Average density of 1500 kg/m^3
Decommissioning Wastes (Type 4 & 6)	326 000	7.72E+07	Average density of 237.3 kg/m^3 (a)
Bulk Waste (Type 1-4 & 6)	**866 000**	**8.88E+08**	
Packaged Waste (Type 5)	**134 000**	**6.86E+07**	Recorded Mass for Waste Package in Waste Database

Note a: The density of 272.3 kg/m^3 is representative of the raw, unprocessed decommissioning waste since the construction material of many historical CRL buildings is primarily wood and there will be significant voids when this construction debris is containerized. The density is sourced from the California's Department of Resources Recycling and Recovery (CalRecycle) [20] and was benchmarked against actual data from decommissioning projects [21].

3.4 Waste Inventory Screening Criteria

Assembled radionuclide data from environmental remediation projects, decommissioning projects and packaged waste was screened through the radionuclide concentration limits of the NSDF WAC [22] as provided below Table 4. Nonetheless, this exercise does not qualify any existing waste for the NSDF; all waste will need to be evaluated against all requirements of the licensed NSDF.

Table 4
NSDF WAC - Radionuclide Concentration Limits in Waste

Limits for Bulk Waste & Non-Leachate Controlled Packaged Waste	- 100 Bq/g for α emitting radionuclides - 1,000 Bq/g for long-lived βϒ emitting radionuclides ($t_{1/2}$ > Cs-137) - 10,000 Bq/g for short-lived βϒ emitting radionuclides ($t_{1/2}$ ≤ Cs-137) - 100,000 Bq/g for H-3
Limits for Leachate Controlled Packaged Waste	- 400 Bq/g for α emitting radionuclides - 10,000 Bq/g for long-lived βϒ emitting radionuclides ($t_{1/2}$ > Cs-137) - 10,000 Bq/g for Cs-137 - 10,000 Bq/g for Sr-90 - 10,000,000 Bq/g for H-3

4. SPECIFIC RADIONUCLIDE INFORMATION

The WAC for current CNL waste management storage facilities are limited predominantly by operational or handling hazards like package exposure rate and criticality safety. As a result, there are gaps in the available analytical data for waste compared to what would be required for a disposal assessment.

In fuel-cycle generated wastes, the full suite of radionuclides are present at generation; however in waste, they may have decayed to concentrations that are below detection limits. Due to the variety of activities at the CNL sites, radionuclide concentrations of the wastes cannot be summarized by a single fingerprint.

Cs-137 concentrations are the best reported and gamma spectrometry is commonly used to measure waste radioactivity. As such, Cs-137 was used as the basis for scaling difficult-to-measure radioactivity into the NSDF Reference Inventory for decommissioning and environmental remediation wastes.

4.1 Radionuclide Data for Waste Packages in Storage

Canadian Nuclear Laboratories maintains radioactive waste databases of information reported by waste generators for the purpose of tracking information including the volume, mass and radioactivity of waste packages in storage at WMA on the CRL site. For the Reference Inventory, data on waste packages placed in storage from 1995 to 2015 were extracted and analysed from Waste Information Program, Version 3 (WIP-III). This represents approximately 17 500 m^3 of the total of approximately 25 000 m^3 of packaged waste being stored in CRL's WMA B and H at the end of 2015 [23].

The process to extract the data from the radioactive waste database is discussed in Appendix C. There were some gaps in the radioactive waste data that were adjusted, specifically:

- Between 1995 and 2005, characterization data was limited on lower activity waste. Many packages were only entered with dose rates and/or gross alpha and beta measurements. These packages were not usable to establish the source term but subsequently applied the average activity of the waste packages that sorted into the Bulk Waste & Non-Leachate Controlled Packaged Waste radioactive category.
- Conventions used to report Uranium concentrations were inconsistent.
- The radioactive waste database does not decay its radioactivity and as a result, concentrations of progeny like Am-241 from the decay of Pu-241 are not conservatively and accurately represented as compared to the other isotopes of plutonium. Similarly, radionuclides with shorter half-lives such as Cs-137, Sr-90, Co-60, and H-3 are over-estimated in the data.

However, there is also some conservatism in the radionuclide data that was not adjusted:

- Historically, characterization has been done with a focus on worker protection. As such, conservative approaches to developing radionuclide fingerprints such as applying hot-spot values and utilizing the distribution-specific 95th percentile instead of an average (e.g., arithmetic mean, geometric mean) are well documented [19]. This practice over-estimates the actual radioactivity of the waste.
- Waste packages were applied the conservative fingerprints (discussed above) and not scaled based on the exposure rate of individual packages.

- When multiple packages were received as part of the same shipment; the exposure rate of the highest package was applied to the whole shipment [24].
- Prior to the establishment of the Waste Analysis Facility in 2007; waste generated from controlled areas was not able to be monitored with high confidence to be designated for unconditional release [25]. As such, there are waste packages in storage that are free from radioactivity.

4.1.1 Screening the Packaged Waste

The WAC screening sorted packages in CNL's waste inventory programs into the two NSDF packaging categories of Non-Leachate Controlled and Leachate Controlled Waste Packages to establish the packaged waste baseline volume. The distribution of the packaged waste baseline volume and the extrapolated NSDF design volume is provided in Table 5. The packaged waste baseline volume and the extrapolated packaged waste volume that satisfy the WAC concentration limits for bulk waste are shown as bulk volume for simplicity in Table 5 ,but may be emplaced as either packaged or bulk wastes. Additional information on the screening is found in Appendix C.2.

Table 5
Packaged Waste Volume screened by NSDF WAC Radiological Categories

	Non-Leachate Controlled Packaged Waste	Leachate Controlled Packaged Waste	Total of Acceptable	Waste Packages that Exceeds NSDF WAC
Waste Database Packaged Waste Baseline Volume (m^3).	8 686	1 227	9 913	1 852
Waste Database Packaged Waste Baseline Volume plus waste in the Waste Database with limited characterization data [(a)] (m^3).	14 385	1 227	15 612	1 852
Packaged Waste Baseline Volume Extrapolated to NSDF Design (m^3)	122 957	10 490	133 447	n/a
Total Packaged Waste including Stored Liquid Waste Project (m^3)	122 957	10 779	133 737	n/a

Note a: Uncategorized Waste is Waste that was in the Radioactive Waste Database without any recorded radionuclides. Most of this waste only had slight contamination and was assumed it would be characterized as Non-Leachate Controlled Waste Packages.

The radioactive waste database baseline volume of 9 913 m^3 was extrapolated to the NSDF design volume for packaged waste of 133 447 m^3 (133 737 m^3 includes 289 m^3 from the stored liquid waste project), which is an estimate of waste volume generated by the retrieval and characterization of existing stored packages and new volume arising from future generation of operational waste by the same processes at CRL and similar wastes from the other CNL sites (e.g., Whiteshell, Gentilly, Douglas Point and Port Hope). Additional information on the screening is found in Appendix C.2.

4.1.2 Estimating the Packaged Waste Source Term at time of Closure

To determine the Packaged Waste Source Term at time of closure, the packaged waste volume was divided to assume that waste will be emplaced evenly during the 50 years of operations of the NSDF. The radionuclides in each fiftieth of the inventory were then decayed based on the assumed amount of time the waste would be

in the NSDF prior to closure of the last cell (e.g., the first waste emplaced was decayed for 49 years and the last waste emplaced was not decay corrected). Additionally, radionuclide progeny are considered in equilibrium, with the exception of the ingrowth of Am-241 from the decay Pu-241. Additional information on the decay calculation for packaged waste can be found in Appendix C.4 and in the spreadsheet associated with the Reference Inventory [26].

4.1.3 Estimated Radionuclide Source Term for Packaged Waste

The NSDF package waste radionuclide inventory [26] is presented in the following tables:

- Table 6 provides the estimated radionuclide source term of NSDF packaged waste that qualify for the "Bulk" NSDF WAC Packaging Category;
- Table 7 provides the estimated radionuclide source term of NSDF packaged waste that qualify for the "Packaged" NSDF WAC Packaging Category;
- Table 8 provides the estimated radionuclide source term of the entire NSDF packaged waste volume extrapolated to the NSDF design volume of 134 000 m^3 for packages.

The total mass of the waste in packages is extrapolated from the actual package mass recorded in the Radioactive Waste Database.

Table 6
Estimated Radionuclide Source Term of NSDF Non-Leachate Controlled Packaged Waste

Radionuclide	Emplaced		At Closure (~2070)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Ag-108m	2.67E+10	5.75E+00	2.56E+10	5.53E+00
Am-241	3.14E+10	6.76E+00	6.08E+10	1.31E+01
Am-243	4.34E+07	9.35E-03	4.33E+07	9.33E-03
C-14	8.94E+11	1.93E+02	8.92E+11	1.92E+02
Cl-36	4.98E+08	1.07E-01	4.98E+08	1.07E-01
Co-60	4.86E+12	1.05E+03	7.88E+11	1.70E+02
Cs-135	4.70E+08	1.01E-01	4.70E+08	1.01E-01
Cs-137	4.45E+12	9.58E+02	2.67E+12	5.76E+02
H-3	2.03E+14	4.38E+04	6.98E+13	1.50E+04
I-129	3.46E+09	7.45E-01	3.46E+09	7.45E-01
Mo-93	6.09E+04	1.31E-05	6.06E+04	1.31E-05
Nb-94	2.25E+09	4.86E-01	2.25E+09	4.85E-01
Ni-59	3.01E+08	6.48E-02	3.01E+08	6.48E-02
Ni-63	6.29E+10	1.36E+01	5.34E+10	1.15E+01
Np-237	1.50E+07	3.24E-03	1.50E+07	3.24E-03
Pu-239/240	3.06E+10	6.58E+00	3.05E+10	6.58E+00
Pu-241	1.36E+12	2.93E+02	5.26E+11	1.13E+02
Pu-242	5.04E+07	1.09E-02	5.04E+07	1.09E-02
Ra-226	3.22E+10	6.95E+00	3.19E+10	6.87E+00
Se-79	8.07E+07	1.74E-02	8.07E+07	1.74E-02
Sn-126	1.08E+08	2.33E-02	1.08E+08	2.33E-02
Sr-90	5.09E+12	1.10E+03	3.00E+12	6.46E+02
Tc-99	1.94E+10	4.19E+00	1.94E+10	4.19E+00
Th-230	3.70E+09	7.98E-01	3.70E+09	7.98E-01
Th-232	1.50E+10	3.23E+00	1.50E+10	3.23E+00
U-233	2.11E+08	4.55E-02	2.11E+08	4.55E-02
U-234	3.04E+10	6.54E+00	3.04E+10	6.54E+00
U-235	1.17E+09	2.52E-01	1.17E+09	2.52E-01
U-238	2.27E+10	4.88E+00	2.27E+10	4.88E+00
Zr-93	2.91E+11	6.28E+01	2.91E+11	6.28E+01

Note a: Concentration calculated using the total package waste mass of 6.40E+07 kg.

Table 7
Estimated Radionuclide Source Term of NSDF Leachate Controlled Packaged Waste

Radionuclide	Emplaced		At Closure (~2070)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Ag-108m	6.24E+08	1.34E-01	5.99E+08	1.29E-01
Am-241	1.66E+10	3.57E+00	1.83E+10	3.93E+00
Am-243	2.80E+06	6.02E-04	2.79E+06	6.01E-04
C-14	6.08E+11	1.31E+02	6.06E+11	1.31E+02
Cl-36	2.90E+09	6.25E-01	2.90E+09	6.25E-01
Co-60	9.06E+16	1.95E+07	1.47E+16	3.16E+06
Cs-135	4.04E+07	8.70E-03	4.04E+07	8.70E-03
Cs-137	4.67E+11	1.01E+02	2.81E+11	6.06E+01
H-3	5.91E+14	1.27E+05	2.03E+14	4.38E+04
I-129	2.66E+10	5.74E+00	2.66E+10	5.74E+00
Mo-93	6.98E+04	1.50E-05	6.95E+04	1.50E-05
Nb-94	1.87E+10	4.02E+00	1.87E+10	4.02E+00
Ni-59	7.70E+08	1.66E-01	7.70E+08	1.66E-01
Ni-63	2.13E+11	4.58E+01	1.80E+11	3.88E+01
Np-237	2.39E+05	5.16E-05	2.39E+05	5.16E-05
Pu-239/240	4.68E+10	1.01E+01	4.68E+10	1.01E+01
Pu-241	1.03E+11	2.22E+01	3.98E+10	8.57E+00
Pu-242	5.09E+06	1.10E-03	5.09E+06	1.10E-03
Ra-226	4.05E+09	8.73E-01	4.01E+09	8.64E-01
Se-79	5.82E+05	1.25E-04	5.82E+05	1.25E-04
Sn-126	9.06E+05	1.95E-04	9.06E+05	1.95E-04
Sr-90	2.20E+11	4.75E+01	1.30E+11	2.80E+01
Tc-99	2.97E+11	6.40E+01	2.97E+11	6.40E+01
Th-230	7.97E+08	1.72E-01	7.97E+08	1.72E-01
Th-232	8.88E+09	1.91E+00	8.88E+09	1.91E+00
U-233	2.96E+07	6.39E-03	2.96E+07	6.39E-03
U-234	2.91E+10	6.26E+00	2.91E+10	6.26E+00
U-235	1.40E+09	3.02E-01	1.40E+09	3.02E-01
U-238	4.45E+10	9.60E+00	4.45E+10	9.60E+00
Zr-93	1.43E+11	3.09E+01	1.43E+11	3.09E+01

Note a: Concentration calculated using the total package waste mass of 4.64E+06 kg.

Table 8
Estimated Radionuclide Source Term of NSDF Packaged Waste

Radionuclide	Emplaced		At Closure (~2070)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Ag-108m	2.73E+10	3.98E-01	2.62E+10	3.83E-01
Am-241	4.80E+10	6.99E-01	7.90E+10	1.15E+00
Am-243	4.62E+07	6.73E-04	4.61E+07	6.72E-04
C-14	1.50E+12	2.19E+01	1.50E+12	2.18E+01
Cl-36	3.40E+09	4.96E-02	3.40E+09	4.96E-02
Co-60	9.06E+16	1.32E+06	1.47E+16	2.14E+05
Cs-135	5.10E+08	7.43E-03	5.10E+08	7.43E-03
Cs-137	4.91E+12	7.16E+01	2.95E+12	4.31E+01
H-3	7.94E+14	1.16E+04	2.73E+14	3.98E+03
I-129	3.01E+10	4.39E-01	3.01E+10	4.39E-01
Mo-93	1.31E+05	1.91E-06	1.30E+05	1.90E-06
Nb-94	2.09E+10	3.05E-01	2.09E+10	3.05E-01
Ni-59	1.07E+09	1.56E-02	1.07E+09	1.56E-02
Ni-63	2.75E+11	4.01E+00	2.34E+11	3.41E+00
Np-237	1.53E+07	2.22E-04	1.53E+07	2.22E-04
Pu-239/240	7.74E+10	1.13E+00	7.73E+10	1.13E+00
Pu-241	1.46E+12	2.13E+01	5.65E+11	8.24E+00
Pu-242	5.55E+07	8.09E-04	5.55E+07	8.09E-04
Ra-226	3.63E+10	5.29E-01	3.59E+10	5.23E-01
Se-79	8.13E+07	1.18E-03	8.13E+07	1.18E-03
Sn-126	1.09E+08	1.59E-03	1.09E+08	1.59E-03
Sr-90	5.31E+12	7.74E+01	3.13E+12	4.55E+01
Tc-99	3.16E+11	4.61E+00	3.16E+11	4.61E+00
Th-230	4.50E+09	6.56E-02	4.50E+09	6.56E-02
Th-232	2.39E+10	3.48E-01	2.39E+10	3.48E-01
U-233	2.41E+08	3.51E-03	2.41E+08	3.51E-03
U-234	5.94E+10	8.66E-01	5.94E+10	8.66E-01
U-235	2.57E+09	3.75E-02	2.57E+09	3.75E-02
U-238	6.72E+10	9.79E-01	6.72E+10	9.79E-01
Zr-93	4.35E+11	6.34E+00	4.35E+11	6.34E+00

Note a: Concentration calculated using the total package waste mass of 6.86E+07 kg.

4.2 Radionuclide Data for Bulk Waste

4.2.1 Decommissioning Waste

Radionuclide data from scoping and investigations for decommissioning waste is available for some structures on the CRL site and one structure (Building 107) that has been demolished. Data obtained from this work was used to refine the estimated radioactivity for the decommissioning wastes. The forecast volume and radioactivity for decommissioning waste generation arose from data collected from the following structures:

- Building 107 [27].
- Building 204 J-Rod Bays [28].
- Building 204 Process Piping [29].

As in packaged wastes, Cs-137 concentrations were the most consistently reported radionuclide for decommissioning waste forecasts. Inconsistencies in the data are present and required adjustment prior to use, detail regarding adjustments to this data is provided in section 4.2.3. Examples of data inconsistencies in decommissioning waste forecasts include:

- Surface radioactivity concentrations were applied to volumetric waste streams like contaminated concrete which resulted in over-estimates.
- Radionuclide concentrations were reported for a limited number of radionuclides due to reliance on mainly gamma spectroscopy.
- Conventions used to report Uranium concentrations were inconsistent.
- Fission and activation product radionuclides were inconsistently reported.

An estimated 326 000 m^3 of waste is forecast to be generated by decommissioning projects across CNL.

4.2.2 Environmental Remediation Waste

The affected land areas are the result historical practices that included direct disposal of radioactive materials with limited and/or no containment and the dispersion of Low-Level Radioactive Liquids onto soils. These practices led to variability in the radionuclide distribution due to deposition and dispersion. As an example, insoluble radionuclides remain largely in place, whereas soluble radionuclides have migrated some distances from the point of deposition.

An estimated 541 000 m^3 of soil, co-mingled soil and debris and organic debris is estimated to be generated by environmental remediation projects across AECL sites that will likely meet the acceptance criteria for NSDF. Wastes to be generated by environmental remediation of impacted soils on AECL sites like CRL and Whiteshell Laboratories are contaminated for the most part with fuel-cycle radionuclides.

When the Reference Inventory was generated, only initial scoping surveys had been completed for some of the envisioned environmental remediation projects. Two examples were Liquid Dispersal Areas (LDA) - Reactor Pit #1 and Chemical Pit [30] and Nitrate Plant [31]; however, most of the characterization was performed around the source term and not representative of the entire area that required remediation.

The early characterization did not include the whole suite of radionuclides identified for a post-closure safety assessment. Cesium-137 radioactivity concentrations reported in the environmental remediation projects forecast data were judged to be the most reliable; therefore, representative Cs-137 activities from environmental remediation projects were scaled against the waste package inventory to be able to create the

estimated source term for environmental remediation waste, as with the decommissioning waste discussed in Section 1.1.1.

In addition to the fuel cycle waste, the CRL site is currently storing WMA F approximately 60 500 m^3 of soil wastes resulting from uranium, radium and niobium refining waste that was shipped to Chalk River during the 1970s [19]. As this waste is not representative of fuel cycle waste, initial characterization data was analysed and incorporated into the estimated source term for bulk waste.

4.2.3 Estimating the Bulk Waste at time of Closure

The radioactivity of parent radionuclides in the bulk waste are decreasing because no additional source material is being added to the non-operating facilities and WMAs that make up most of the source of bulk waste. To estimate the total activity associated with bulk waste, the source term was decayed for 50 years, the operating period of NSDF. Radionuclide progeny are considered in equilibrium where applicable, except for the ingrowth of Am-241 from the decay Pu-241. Additional information on the decay calculation for bulk waste can be found in Appendix C.4 and in the spreadsheet associated with the Reference Inventory [26].

4.2.4 Scaling Factor for Bulk Waste.

As discussed earlier, there are gaps in the available analytical data for waste compared to what would be required for disposal assessment. Cesium-137 is considered to be the most reliable radionuclide concentration in the source data and is commonly used as the basis for scaling hard-to-measure radioactivity into a waste stream. Although Am-241 is also helpful for scaling actinides when it is fully built-in (50-70 years). After adjustments were made, Cs-137 scaling factors were derived from the waste packages radioactivity to inform the radionuclide distribution in under-reported (with respect to radionuclide concentrations important to waste disposal decisions at the NSDF) waste streams.

Adjustments were made to Cs-135, I-129, and Zr-93 packaged waste concentrations as they were obvious outliers when compared to their actual production potential estimated from ratios depicted in high burn-up fuels used by CNL waste generating processes.

The resulting radionuclide ratios (i.e., scaling factors) were compared against anticipated radionuclide distribution, side-by-side comparison to example scaling factors from ORIGEN data at T=50y, and scaling factors observed to date in environmental remediation data. The scaling factors applied to bulk waste forecast Cs-137 radioactivity and the side-by-side comparisons are provided below in Table 9 [32].

A qualitative assessment of scaling factors is found in Appendix D.

Table 9
Environmental Remediation and Decommissioning Projects Scaling Factors

Radionuclide	Cs-137 scaling factors	Scaling Factors Specific ORIGEN Runs at T=50 years	Observed in Environmental Remediation Data
Ag-108m	2.77E-08		
Am-241	1.85E-02	1.20E-03	2.22E-02
Am-243	9.45E-06		
C-14	3.06E-01		

Radionuclide	Cs-137 scaling factors	Scaling Factors Specific ORIGEN Runs at T=50 years	Observed in Environmental Remediation Data
Cl-36	8.50E-04		
Co-60	1.75E+01		
Cs-135	1.42E-05	3.07E-06	
Cs-137	1.00E+00		
H-3	1.44E+02		
I-129	2.39E-04	7.20E-07	
Mo-93	2.47E-08		
Nb-94	3.70E-02		
Ni-59	2.06E-04		
Ni-63	5.24E-02		
Np-237	3.14E-06		
Pu-239/240	1.53E-02		3.55E-02
Pu-241	2.99E-01		
Pu-242	1.14E-05		
Ra-226	7.36E-03		
Se-79	1.68E-05		
Sn-126	2.25E-05	6.85E-06	
Sr-90	1.09E+00		
Tc-99	9.50E-05	4.28E-04	
Th-230	9.03E-04		
Th-232	4.63E-03		
U-233	4.88E-05		
U-234	1.36E-02		
U-235	4.86E-04		
U-238	1.24E-02		
Zr-93	2.08E-01		

4.2.5 Estimated Radionuclide Source Term for Bulk Waste

The NSDF Bulk Waste radionuclide inventory is presented in the following tables [26]:

- Table 10 provides the estimated radionuclide source term for the decommissioning and environmental remediation projects waste volume to be disposed in the NSDF;
- Table 11 provides the estimated radionuclides source term for all waste that qualifies as bulk waste for NSDF disposal, including packaged waste, decommissioning and environmental remediation waste.

Since the development of the Reference Inventory, additional characterization has occurred at CRL and at Whiteshell Laboratories on decommissioning and environmental remediation projects. This new characterization data is presented in Appendix E.

Table 10
Estimated Radionuclide Source Term of Decommissioning and Environmental Remediation Project Waste for NSDF

Radionuclide	Emplaced		At Closure (50 years of Decay)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Ag-108m	1.87E+04	2.11E-08	1.72E+04	1.94E-08
Am-241	1.25E+10	1.41E-02	1.84E+10	2.07E-02
Am-243	6.38E+06	7.18E-06	6.35E+06	7.15E-06
C-14	2.07E+11	2.33E-01	2.05E+11	2.31E-01
Cl-36	5.74E+08	6.46E-04	5.74E+08	6.46E-04
Co-60	1.18E+13	1.33E+01	1.65E+10	1.86E-02
Cs-135	9.59E+06	1.08E-05	9.59E+06	1.08E-05
Cs-137	6.75E+11	7.60E-01	2.14E+11	2.41E-01
H-3	9.75E+13	1.10E+02	5.85E+12	6.59E+00
I-129	1.62E+08	1.82E-04	1.62E+08	1.82E-04
Mo-93	1.67E+04	1.88E-08	1.65E+04	1.86E-08
Nb-94	2.50E+09	2.82E-03	2.50E+09	2.81E-03
Ni-59	1.39E+08	1.57E-04	1.39E+08	1.57E-04
Ni-63	3.54E+10	3.98E-02	2.50E+10	2.82E-02
Np-237	2.12E+06	2.39E-06	2.12E+06	2.39E-06
Pu-239/240	1.03E+10	1.16E-02	1.03E+10	1.16E-02
Pu-241	2.02E+11	2.27E-01	1.81E+10	2.03E-02
Pu-242	7.68E+06	8.64E-06	7.68E+06	8.64E-06
Ra-226	1.92E+08	2.16E-04	1.87E+08	2.11E-04
Se-79	1.13E+07	1.28E-05	1.13E+07	1.28E-05
Sn-126	1.52E+07	1.71E-05	1.52E+07	1.71E-05
Sr-90	7.36E+11	8.29E-01	2.21E+11	2.49E-01
Tc-99	6.42E+07	7.23E-05	6.42E+07	7.22E-05
Th-230	8.01E+08	9.02E-04	8.01E+08	9.02E-04
Th-232	3.15E+09	3.54E-03	3.15E+09	3.54E-03
U-233	3.29E+07	3.71E-05	3.29E+07	3.71E-05

Radionuclide	Emplaced		At Closure (50 years of Decay)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
U-234	9.34E+09	1.05E-02	9.34E+09	1.05E-02
U-235	3.91E+08	4.40E-04	3.91E+08	4.40E-04
U-238	8.54E+09	9.62E-03	8.54E+09	9.62E-03
Zr-93	5.72E+10	6.45E-02	5.72E+10	6.45E-02

Note a: Concentration calculated using the total bulk waste mass of 8.88E+08 kg.

Table 11
Estimated Radionuclide Source Term of Bulk Waste and Non-Leachate Controlled Waste Packages for NSDF Disposal

Radionuclide	Emplaced		At Closure (50 years of Decay)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Ag-108m	2.67E+10	2.80E-02	2.56E+10	2.69E-02
Am-241	4.39E+10	4.61E-02	7.92E+10	8.32E-02
Am-243	4.98E+07	5.23E-05	4.96E+07	5.21E-05
C-14	1.10E+12	1.16E+00	1.10E+12	1.15E+00
Cl-36	1.07E+09	1.13E-03	1.07E+09	1.13E-03
Co-60	1.67E+13	1.75E+01	8.04E+11	8.45E-01
Cs-135	4.79E+08	5.03E-04	4.79E+08	5.03E-04
Cs-137	5.12E+12	5.38E+00	2.89E+12	3.03E+00
H-3	3.01E+14	3.16E+02	7.56E+13	7.94E+01
I-129	3.62E+09	3.80E-03	3.62E+09	3.80E-03
Mo-93	7.76E+04	8.15E-08	7.72E+04	8.11E-08
Nb-94	4.75E+09	4.99E-03	4.75E+09	4.99E-03
Ni-59	4.40E+08	4.62E-04	4.40E+08	4.62E-04
Ni-63	9.83E+10	1.03E-01	7.84E+10	8.23E-02
Np-237	1.71E+07	1.80E-05	1.71E+07	1.80E-05
Pu-239/240	4.09E+10	4.29E-02	4.08E+10	4.29E-02
Pu-241	1.56E+12	1.64E+00	5.44E+11	5.71E-01
Pu-242	5.81E+07	6.10E-05	5.81E+07	6.10E-05
Ra-226	3.24E+10	3.41E-02	3.21E+10	3.37E-02
Se-79	9.21E+07	9.67E-05	9.20E+07	9.67E-05
Sn-126	1.23E+08	1.29E-04	1.23E+08	1.29E-04
Sr-90	5.83E+12	6.12E+00	3.22E+12	3.38E+00
Tc-99	1.95E+10	2.05E-02	1.95E+10	2.05E-02
Th-230	4.50E+09	4.73E-03	4.50E+09	4.73E-03
Th-232	1.81E+10	1.90E-02	1.81E+10	1.90E-02
U-233	2.44E+08	2.56E-04	2.44E+08	2.56E-04
U-234	3.97E+10	4.17E-02	3.97E+10	4.17E-02
U-235	1.56E+09	1.64E-03	1.56E+09	1.64E-03
U-238	3.12E+10	3.28E-02	3.12E+10	3.28E-02

Radionuclide	Emplaced		At Closure (50 years of Decay)	
	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]	Total Activity (Bq)	Averaged Activity Concentration (Bq/g)[(a)]
Zr-93	3.49E+11	3.66E-01	3.49E+11	3.66E-01

Note a: Concentration calculated using the total bulk waste mass of 9.52E+08 kg.

5. ASSUMED RADIONUCLIDE INVENTORY

Long-lived radionuclides are included in the NSDF inventory as they are intrinsically part of the radiological fingerprints of waste streams at CRL and other CNL sites. It is not practical, technical or economical, to separate the long-lived radionuclides from the waste streams. However, the concentrations of long-lived radionuclides that are proposed in the NSDF reference inventory are consistent with Canadian Standards Association (CSA) [33] and International Atomic Energy Agency (IAEA) guidance [34]. Furthermore, the risk that this radioactive material presents to the public and environment is studied in detail in post-closure safety modelling to ensure the dose consequence and environmental concentrations meet the dose acceptance criteria and environmental quality standards [13].

The post closure safety assessment modelling is used to refine the radiological inventory. During this iterative process, a decision was made to adjust the concentrations of many long-lived radionuclides to ensure that the total radioactivity in the NSDF decays to near-background levels within a reasonable timeframe. As a result, the acceptable quantity of Zr-93 was reduced to 40.8% and Nb-94 was reduced to 10% of the original values. Table 12 below represents the NSDF Reference Inventory.

At CNL, Pu-239 and Pu-240 are reported together and is treated as Pu-239 in the Post-Closure Safety Assessment [13]. This is a common industry practice in decommissioning and waste characterization and conservative because the Pu-240 and Pu-239 dose factors are similar, however Pu-239 half-life is longer.

Table 12
NSDF Reference Inventory and Concentrations at Emplacement and at Closure

	NSDF Reference Inventory at Emplacement		NSDF Reference Inventory at Closure	
Radionuclide	**Total Activity (Bq)**	**Averaged Activity Concentration (Bq/g)[(a)]**	**Total Activity (Bq)**	**Averaged Activity Concentration (Bq/g)[(a)]**
Ag-108m	2.73E+10	2.86E-02	2.62E+10	2.74E-02
Am-241	6.04E+10	6.32E-02	9.74E+10	1.02E-01
Am-243	5.26E+07	5.49E-05	5.24E+07	5.48E-05
C-14	1.71E+12	1.79E+00	1.70E+12	1.78E+00
Cl-36	3.97E+09	4.15E-03	3.97E+09	4.15E-03
Co-60	9.06E+16	9.47E+04	1.47E+16	1.53E+04
Cs-135	5.19E+08	5.43E-04	5.19E+08	5.43E-04
Cs-137	5.59E+12	5.84E+00	3.17E+12	3.31E+00
H-3	8.91E+14	9.32E+02	2.79E+14	2.91E+02
I-129	3.03E+10	3.16E-02	3.03E+10	3.16E-02
Mo-93	1.47E+05	1.54E-07	1.47E+05	1.53E-07
Nb-94	2.34E+10	2.45E-02	2.34E+10	2.45E-02
Ni-59	1.21E+09	1.26E-03	1.21E+09	1.26E-03
Ni-63	3.11E+11	3.25E-01	2.59E+11	2.70E-01
Np-237	1.74E+07	1.82E-05	1.74E+07	1.82E-05
Pu-239/240	8.77E+10	9.16E-02	8.76E+10	9.16E-02
Pu-241	1.67E+12	1.74E+00	5.84E+11	6.10E-01
Pu-242	6.32E+07	6.60E-05	6.32E+07	6.61E-05
Ra-226	3.65E+10	3.81E-02	3.61E+10	3.77E-02
Se-79	9.26E+07	9.68E-05	9.26E+07	9.68E-05

	NSDF Reference Inventory at Emplacement		NSDF Reference Inventory at Closure	
Radionuclide	**Total Activity (Bq)**	**Averaged Activity Concentration (Bq/g)[(a)]**	**Total Activity (Bq)**	**Averaged Activity Concentration (Bq/g)[(a)]**
Sn-126	1.24E+08	1.30E-04	1.24E+08	1.30E-04
Sr-90	6.05E+12	6.32E+00	3.35E+12	3.50E+00
Tc-99	3.16E+11	3.31E-01	3.16E+11	3.31E-01
Th-230	5.30E+09	5.54E-03	5.30E+09	5.54E-03
Th-232	2.70E+10	2.82E-02	2.70E+10	2.82E-02
U-233	2.74E+08	2.86E-04	2.74E+08	2.86E-04
U-234	6.88E+10	7.19E-02	6.88E+10	7.19E-02
U-235	2.96E+09	3.10E-03	2.96E+09	3.10E-03
U-238	7.57E+10	7.91E-02	7.57E+10	7.92E-02
Zr-93	4.92E+11	5.14E-01	4.92E+11	5.17E-01

Note a: Average activity concentrations calculated using the Engineered Containment Mound total waste mass of 9.57E+08 kg.

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[32] *Facilities Decommissioning and Environmental Remediation Radionuclide Estimates used for the NSDF Reference Inventory*, 232-509240-021-000-0010, Revision 0, 232-509240-021-000-0010

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[34] *Classification of Radioactive Waste*, General Safety Guide No. GSG-1, International Atomic Energy Agency, November 2009.

APPENDIX A RADIONUCLIDES REPORTED IN CNL WASTE DATABASE

Table A-1 lists all radionuclides recorded in CNL's Waste Inventory Programs, Version 3 (WIP-III) from 1995 to 2015. The half-life is from the International Atomic Energy Agency Chart of the Nuclides [18].

Table A-1
Radionuclides in the Waste Inventory Program, Version III (WIP-III)

Radionuclides in WIP-III Data	Element	Half-Life [18]		Included in the NSDF Inventory
Ac-227	Actinium	21.77	years	
Ac-228	Actinium	6.15	hours	
Ag-108m	Silver	438.00	years	x
Ag-110	Silver	24.56	seconds	
Ag-110m	Silver	249.83	days	
Ag-111	Silver	7.45	days	
Al-26	Aluminum	7.17E+05	years	
Am-241	Americium	432.60	years	x
Am-242m	Americium	141.00	years	
Am-243	Americium	7.36E+03	years	x
Ar-39	Argon	269.00	years	
Ar-42	Argon	32.90	years	
Au-195	Gold	186.01	days	
Ba-133	Barium	10.55	years	
Ba-133m	Barium	38.93	hours	
Ba-140	Barium	12.75	days	
Be-07	Beryllium	53.22	days	
Be-10	Beryllium	1.51E+06	years	
Bi-207	Bismuth	31.55	years	
Bi-210	Bismuth	5.01	days	
Bi-214	Bismuth	19.90	minutes	
Bi-217	Bismuth	98.50	seconds	
C-14	Carbon	5.70E+03	years	x
Ca-41	Calcium	1.02E+05	years	
Ca-45	Calcium	162.61	days	
Cd-109	Cadmium	461.40	days	
Cd-113m	Cadmium	14.10	years	
Cd-115m	Cadmium	44.56	days	
Ce-139	Cerium	137.64	days	
Ce-141	Cerium	32.51	days	
Ce-144	Cerium	284.91	days	
Cf-252	Californium	2.65	years	
Cl-36	Chlorine	3.01E+05	years	x
Cm-242	Curium	162.80	days	

Radionuclides in WIP-III Data	Element	Half-Life [18]	Included in the NSDF Inventory
Cm-243	Curium	29.10 years	
Cm-244	Curium	18.10 years	
Cm-245	Curium	8.42E+03 years	
Cm-246	Curium	4.71E+03 years	
Co-56	Cobalt	77.24 days	
Co-57	Cobalt	271.74 days	
Co-58	Cobalt	70.86 days	
Co-60	Cobalt	1.93E+03 days	x
Cr-51	Chromium	27.70 days	
Cs-134	Cesium	2.07 years	
Cs-135	Cesium	2.30E+06 years	x
Cs-136	Cesium	13.16 days	
Cs-137	Cesium	30.08 years	x
Dy-159	Dysprosium	144.40 days	
Eu-149	Europium	93.10 days	
Eu-152	Europium	13.52 years	
Eu-154	Europium	8.60 years	
Eu-155	Europium	4.75 years	
Eu-156	Europium	15.19 days	
Fe-55	Iron	2.74 years	
Fe-59	Iron	44.50 days	
Ga-67	Gallium	3.26 days	
Gd-148	Gadolinium	71.10 years	
Gd-151	Gadolinium	123.90 days	
Gd-153	Gadolinium	240.40 days	
Ge-68	Germanium	270.93 days	
H-3	Hydrogen	12.32 years	x
Hf-172	Hafnium	1.87 years	
Hf-175	Hafnium	70.00 days	
Hf-178m	Hafnium	31.00 years	
Hf-181	Hafnium	42.39 days	
Hg-203	Mercury	46.59 days	
Ho-163	Holmium	4.57E+03 years	
Ho-166m	Holmium	1.20E+03 years	
I-125	Iodine	59.41 days	
I-126	Iodine	12.93 days	
I-129	Iodine	1.57E+07 years	x
I-131	Iodine	8.03 days	
In-111	Indium	2.80 days	
Ir-192	Iridium	73.83 days	

Radionuclides in WIP-III Data	Element	Half-Life [18]		Included in the NSDF Inventory
K-40	Potassium	1.25E+09	years	
Kr-85	Krypton	10.74	years	
La-140	Lanthanum	1.68	days	
Lu-173	Lutetium	1.37	years	
Lu-174	Lutetium	3.31	years	
Lu-174m	Lutetium	142.00	days	
Lu-177	Lutetium	6.65	days	
Lu-177m	Lutetium	160.44	days	
Mn-54	Manganese	312.20	days	
Mn-56	Manganese	2.58	hours	
Mo-93	Molybdenum	4.00E+03	years	x
Mo-99	Molybdenum	65.98	hours	
Na-22	Sodium	2.60	years	
Na-24	Sodium	15.00	hours	
Nb-91	Niobium	680.00	years	
Nb-91m	Niobium	60.86	days	
Nb-92m	Niobium	10.15	days	
Nb-93m	Niobium	16.12	years	
Nb-94	Niobium	2.03E+04	years	x
Nb-95	Niobium	34.99	days	
Nb-97	Niobium	72.10	minutes	
Ni-59	Nickel	7.60E+04	years	x
Ni-63	Nickel	101.20	years	x
Np-237	Neptunium	2.14E+06	years	x
Np-239	Neptunium	2.36	days	
P-32	Phosphorus	14.27	days	
P-33	Phosphorus	25.35	days	
Pa-231	Protactinium	3.28E+04	years	
Pa-233	Protactinium	26.98	days	
Pa-234	Protactinium	6.70	hours	
Pa-234m	Protactinium	1.16	minutes	
Pb-210	Lead	22.20	years	
Pb-211	Lead	36.10	minutes	
Pb-212	Lead	10.64	hours	
Pb-214	Lead	27.06	minutes	
Pd-103	Palladium	16.99	days	
Pd-107	Palladium	6.50E+06	years	
Pm-143	Promethium	265.00	days	
Pm-145	Promethium	17.70	years	
Pm-146	Promethium	5.53	years	

Radionuclides in WIP-III Data	Element	Half-Life [18]	Included in the NSDF Inventory
Pm-147	Promethium	2.62 years	
Po-208	Polonium	2.90 years	
Po-209	Polonium	125.20 years	
Po-210	Polonium	138.38 days	
Pr-144	Praseodymium	17.28 minutes	
Pu-236	Plutonium	2.86 years	
Pu-237	Plutonium	45.64 days	
Pu-238	Plutonium	87.70 years	
Pu-239	Plutonium	2.41E+04 years	x
Pu-240	Plutonium	6.56E+03 years	x[(a)]
Pu-241	Plutonium	14.29 years	x
Pu-242	Plutonium	3.75E+05 years	
Ra-223	Radium	11.43 days	
Ra-226	Radium	1.60E+03 years	x
Ra-228	Radium	5.75 years	
Rb-83	Rubidium	86.20 days	
Rb-84	Rubidium	32.82 days	
Rb-86	Rubidium	18.64 days	
Re-187	Rhenium	4.33E+10 years	
Rh-101	Rhodium	3.30 years	
Rh-102	Rhodium	207.30 days	
Rh-102m	Rhodium	3.74 years	
Rh-106	Rhodium	30.07 seconds	
Ru-103	Ruthenium	39.25 days	
Ru-106	Ruthenium	371.80 days	
S-35	Sulfur	87.37 days	
Sb-122	Antimony	2.72 days	
Sb-124	Antimony	60.20 days	
Sb-125	Antimony	2.76 years	
Sb-126	Antimony	12.35 days	
Sc-46	Scandium	83.79 days	
Se-75	Selenium	119.78 days	
Se-79	Selenium	2.95E+05 years	x
Si-32	Silicon	153.00 years	
Sm-145	Samarium	340.00 days	
Sm-151	Samarium	90.00 years	
Sm-153	Samarium	46.28 hours	
Sn-113	Tin	115.09 days	
Sn-119m	Tin	293.10 days	
Sn-121m	Tin	43.90 years	

Radionuclides in WIP-III Data	Element	Half-Life [18]		Included in the NSDF Inventory
Sn-123m	Tin	40.06	minutes	
Sn-126	Tin	2.30E+05	years	x
Sr-82	Strontium	23.35	days	
Sr-85	Strontium	64.85	days	
Sr-89	Strontium	50.56	days	
Sr-90	Strontium	28.79	years	x
Ta-179	Tantalum	1.82	years	
Ta-182	Tantalum	114.74	days	
Tb-157	Terbium	71.00	years	
Tb-160	Terbium	72.30	days	
Tc-99	Technetium	2.11E+05	years	x
Tc-99m	Technetium	6.01	hours	
Te-121	Tellurium	19.17	days	
Te-121m	Tellurium	164.20	days	
Te-123	Tellurium	9.20E+16	years	
Te-123m	Tellurium	119.20	days	
Te-127	Tellurium	9.35	hours	
Te-127m	Tellurium	106.10	days	
Te-129	Tellurium	69.60	minutes	
Te-129m	Tellurium	33.60	days	
Te-131m	Tellurium	33.25	hours	
Te-132	Tellurium	3.20	days	
Th-227	Thorium	18.68	days	
Th-228	Thorium	1.91	years	
Th-230	Thorium	7.54E+04	years	x
Th-232	Thorium	1.40E+10	years	x
Th-234	Thorium	24.10	days	
Ti-44	Titanium	59.10	years	
Tl-201	Thallium	3.04	days	
Tl-204	Thallium	3.78	years	
Tl-208	Thallium	3.05	minutes	
Tm-168	Thulium	93.10	days	
Tm-170	Thulium	128.60	days	
U-232	Uranium	68.90	years	
U-233	Uranium	1.59E+05	years	x
U-234	Uranium	2.46E+05	years	x
U-235	Uranium	7.04E+08	years	x
U-236	Uranium	2.34E+07	years	
U-238	Uranium	4.47E+09	years	x
V-49	Vanadium	330.00	days	

Radionuclides in WIP-III Data	Element	Half-Life [18]	Included in the NSDF Inventory
W-181	Tungsten	121.20 days	
Xe-133	Xenon	5.25 days	
Xe-135	Xenon	9.14 hours	
Y-88	Yttrium	106.63 days	
Y-90	Yttrium	64.00 hours	
Y-91	Yttrium	58.51 days	
Yb-169	Ytterbium	32.02 days	
Zn-65	Zinc	243.93 days	
Zr-88	Zirconium	83.40 days	
Zr-93	Zirconium	1.61E+06 years	x
Zr-95	Zirconium	64.03 days	

Note a: Included as Pu-239 as these radionuclides are generally combined in laboratory analysis.

Table A-2 lists the total activity (in becquerels) of radionuclides recorded in the CNL database with half-live greater than five years. The noble gases Ar-39, Ar-42 and Kr-85 were also screened out.

Table A-2
Activity of Radionuclides with Half-Lives Greater than 5 Years Recorded in the Waste Inventory Program, Version III (WIP-III) from 1995 to 2015

Radionuclides with Half-Lives Greater than 5 years [(a)]	Predominate Decay Mode	Total Activity of Packages in the WIP-III Database Sorted as Non-Leachate Controlled Packaged Waste (Bq) [(b)]	Total Activity of Packages in the WIP-III Database Sorted as Leachate Controlled Packaged Waste (Bq) [(c)]	Total Activity of All Packages in the WIP-III Database that were Screened through the NSDF Waste Acceptance Criteria (Bq) [(d)]
Ac-227	alpha	1.05E+07	3.60E+06	1.41E+07
Ag-108m	beta/gamma	**1.89E+09**	**7.30E+07**	**1.96E+09**
Al-26	beta/gamma	1.54E+04	4.70E+04	6.24E+04
Am-241	alpha	**2.22E+09**	**1.01E+09**	**3.23E+09**
Am-242m	beta/gamma	2.93E+04	1.82E+03	3.11E+04
Am-243	alpha	**3.07E+06**	**3.27E+05**	**3.39E+06**
Ba-133	beta/gamma	9.66E+07	3.12E+07	1.28E+08
Be-10	beta/gamma	2.52E-05	0.00E+00	2.52E-05
Bi-207	beta/gamma	3.94E+05	1.30E+06	1.69E+06
C-14	beta/gamma	**6.32E+10**	**6.95E+10**	**1.33E+11**
Ca-41	beta/gamma	3.93E+02	3.54E+01	4.28E+02
Cd-113m	beta/gamma	2.97E+06	4.09E+07	4.38E+07
Cl-36	beta/gamma	**3.51E+07**	**3.15E+08**	**3.50E+08**
Cm-242	alpha	2.43E+07	1.26E+06	2.56E+07
Cm-243	alpha	1.18E+06	1.12E+06	2.30E+06

Radionuclides with Half-Lives Greater than 5 years [a]	Predominate Decay Mode	Total Activity of Packages in the WIP-III Database Sorted as Non-Leachate Controlled Packaged Waste (Bq) [b]	Total Activity of Packages in the WIP-III Database Sorted as Leachate Controlled Packaged Waste (Bq) [c]	Total Activity of All Packages in the WIP-III Database that were Screened through the NSDF Waste Acceptance Criteria (Bq) [d]
Cm-244[e]	alpha	1.13E+08	1.53E+07	1.29E+08
Cm-245	alpha	2.82E+01	1.49E+00	2.97E+01
Cm-246	alpha	4.94E+00	2.60E-01	5.20E+00
Co-60	beta/gamma	**3.43E+11**	**1.06E+16**	**1.06E+16**
Cs-135	beta/gamma	**3.32E+07**	**4.72E+06**	**3.79E+07**
Cs-137	beta/gamma	**3.14E+11**	**5.28E+10**	**3.67E+11**
Eu-152	beta/gamma	3.03E+09	7.67E+08	3.80E+09
Eu-154	beta/gamma	5.38E+09	2.24E+09	7.62E+09
Gd-148	alpha	*There is no reported activity that qualified for NSDF*		
H-3	beta/gamma	**1.43E+13**	**6.91E+13**	**8.34E+13**
Hf-178m	beta/gamma	*There is no reported activity that qualified for NSDF*		
Ho-163	beta/gamma	*There is no reported activity that qualified for NSDF*		
Ho-166M	beta/gamma	7.76E+01	4.09E+00	8.17E+01
I-129	beta/gamma	**2.44E+08**	**3.12E+09**	**3.36E+09**
K-40	beta/gamma	1.26E+09	3.82E+07	1.29E+09
Mo-93	beta/gamma	**4.30E+03**	**8.17E+03**	**1.25E+04**
Nb-91	beta/gamma	0.00E+00	1.65E+08	1.65E+08
Nb-93m	beta/gamma	3.71E+04	2.63E+06	2.67E+06
Nb-94	beta/gamma	**1.59E+09**	**2.18E+10**	**2.34E+10**
Ni-59	beta/gamma	**2.12E+07**	**2.97E+07**	**5.09E+07**
Ni-63	beta/gamma	**4.45E+09**	**1.04E+10**	**1.49E+10**
Np-237	alpha	**1.06E+06**	**2.80E+04**	**1.09E+06**
Pa-231	alpha	3.42E+05	0.00E+00	3.42E+05
Pb-210	beta/gamma	9.00E+07	1.55E+08	2.45E+08
Pd-107	beta/gamma	1.67E+05	1.40E+04	1.81E+05
Pm-145	beta/gamma	*There is no reported activity that qualified for NSDF*		
Pm-146	beta/gamma	1.10E+06	4.98E+06	6.07E+06
Po-209	alpha	1.81E+06	2.19E+06	4.00E+06
Pu-238	alpha	6.93E+08	1.04E+08	7.97E+08
Pu-239	alpha	**2.16E+09**	**6.60E+08**	**2.82E+09**
Pu-240[f]	alpha	**1.29E+09**	**1.31E+08**	**1.42E+09**
Pu-241	beta/gamma	**9.62E+10**	**1.20E+10**	**1.08E+11**
Pu-242	alpha	**3.56E+06**	**2.24E+05**	**3.79E+06**
Ra-226	alpha	**2.28E+09**	**4.74E+08**	**2.75E+09**

Radionuclides with Half-Lives Greater than 5 years [a]	Predominate Decay Mode	Total Activity of Packages in the WIP-III Database Sorted as Non-Leachate Controlled Packaged Waste (Bq) [b]	Total Activity of Packages in the WIP-III Database Sorted as Leachate Controlled Packaged Waste (Bq) [c]	Total Activity of All Packages in the WIP-III Database that were Screened through the NSDF Waste Acceptance Criteria (Bq) [d]
Ra-228	beta/gamma	1.67E+08	2.80E+07	1.95E+08
Re-187	beta/gamma	1.85E+04	0.00E+00	1.85E+04
Se-79	beta/gamma	**5.70E+06**	**5.81E+04**	**5.76E+06**
Si-32	beta/gamma	1.34E+06	3.84E+07	3.98E+07
Sm-151	beta/gamma	1.80E+08	7.60E+09	7.78E+09
Sn-121m	beta/gamma	6.62E+04	2.15E+04	8.76E+04
Sn-126	beta/gamma	**7.63E+06**	**9.02E+04**	**7.72E+06**
Sr-90	beta/gamma	**3.60E+11**	**2.18E+10**	**3.81E+11**
Tb-157	beta/gamma	3.28E+01	1.72E+00	3.45E+01
Tc-99	beta/gamma	**1.37E+09**	**3.47E+10**	**3.61E+10**
Te-123	beta/gamma	1.30E+04	0.00E+00	1.30E+04
Th-230	alpha	**2.62E+08**	**9.32E+07**	**3.55E+08**
Th-232	alpha	**1.06E+09**	**1.04E+09**	**2.10E+09**
Ti-44	beta/gamma	3.19E+06	1.74E+08	1.77E+08
U-232	alpha	6.06E+01	1.31E+00	6.19E+01
U-233	alpha	**1.49E+07**	**3.42E+06**	**1.83E+07**
U-234	alpha	**2.14E+09**	**3.40E+09**	**5.55E+09**
U-235	alpha	**8.27E+07**	**1.64E+08**	**2.47E+08**
U-236	alpha	3.68E+06	2.78E+06	6.45E+06
U-238	alpha	**1.60E+09**	**5.21E+09**	**6.81E+09**
Zr-93	beta/gamma	**5.04E+10**	**4.11E+10**	**9.15E+10**

Note a: Radionuclide in bold are included in the Reference Inventory.
Note b: The volume of packages in WIP-III that sorted as Non-Leachate Controlled Packaged Waste is 8 686 m^3.
Note c: The volume of packages in WIP-III that sorted as Leachate Controlled Packaged Waste is 1 227 m^3.
Note d: The total volume of packages in WIP-III that screened through the NSDF WAC is 9 913 m^3.
Note e: Removed due to expert judgement opinion during the screening process (Section B.1.1.3).
Note f: WIP-III inventory is mostly based on process knowledge (e.g., ORIGEN code) and Pu-240 is reported separately from Pu-239. For the NSDF Reference Inventory Pu-240 are reported as Pu-239/240 as these radionuclides are generally combined in laboratory analysis.

APPENDIX B VERIFICATION OF RADIONUCLIDE SCREENING

[This appendix was originally published as a memo [B-1]

To demonstrate that the radionuclides considered in the analysis are the primary radionuclides contributing to the dose consequence, the following approach was used:

1. Evaluate radionuclides significance:
    - Define dominant pathways.
    - Consider full radionuclide dataset available in CRL' Waste Inventory Program, Version 3 (WIP-III).
    - Rank radionuclides, taking into account activities and dose coefficients corresponding to significant pathways.
    - Consider other factors, such as the effect of decay and in-growth and sorption properties.
2. Compare against similar studies.
3. Determine if the list used in NSDF studies and design is fit for purpose.

B.1 EVALUATION OF SIGNIFICANCE

B.1.1 PRE-CLOSURE

B.1.1.1 Assessment Procedure for Radionuclides Significant to Pre-closure Radiation Dose

This initial list of radionuclides used in the NSDF inventory is limited to isotopes with half-lives over five years (i.e., Table A-2), therefore excluding short-lived fission products, such as I-131 (half-life eight days). This is appropriate as radioactive waste will have spent a minimum of two years in storage or awaiting decommissioning and clean-up prior to transfer to NSDF. In the majority of cases, several decades will have passed from the moment of generation of short-lived fission products to transfer for disposal at NSDF. Short-lived in-growth products, such as Ba-137m, are considered in the analysis in conjunction with their respective parents (e.g., Cs-137).

Depending on accident scenario, significant pathways may include a combination of:

- External exposure
- Ingestion
- Inhalation

For the identification of significant radionuclides that have impact on pre-closure of the NSDF, a quantitative assessment of the assumed NSDF radionuclide inventory was performed by multiplying the total activity for each of radionuclides present in CNL's waste database by the corresponding dose coefficient from International Commission on Radiation Protection (ICRP) document ICRP 119 [B-2] for ingestion and inhalation and a derived dose coefficient from ICRP 107 [B-3] for external dose. The external dose coefficients were derived from gamma energy per disintegration data from ICRP 107 and dose modelling from Nuclear Waste Management Organization, NWMO TR-2012-04 [B-4].

B.1.1.2 Radionuclides significant to external exposure

Radiation exposures for workers will be as low as reasonably achievable and in accordance with NSDF-specific administrative controls. Companywide administrative programs like Radiation Protection and Emergency Response will provide the basis for exposure controlling procedures for NSDF operations, such as:

- Waste acceptance
- Package receipt
- Operations planning/scheduling and off-normal condition procedures.

Radionuclide significance in the context of contributing to external radiation dose was assessed by multiplying total radioactivity for each radionuclide in CNL's waste database by corresponding dose coefficient for representing external exposure. For a typical waste package and radionuclide fingerprint, relative contribution of the gamma emitting radionuclides to the total external dose is presented in Table B-1. It can be seen that in typical CNL waste streams, Co-60 and Cs-137 dominate external exposure risk while packages that bear sources or materials from radionuclide concentrating processes must be evaluated on a case-by case basis to assess and prescribe external dose controls for NSDF workers.

Table B-1
Radionuclide Ranking by External Dose Contribution

Nuclides in WIP-III Database	Ranking by External Dose Contribution, %
Co-60	88.48%
Cs-137	11.51%
All other	<0.01%

B.1.1.3 Radionuclides significant to internal exposure

As for external exposure, radiation protection governance will ensure that under normal operations radionuclide intake is as low as reasonably achievable. Under normal operational conditions, these pathways will be dominated by Radon and gaseous radionuclides (mainly H-3 and C-14), which will be emitted from the NSDF [B-5]. The resulting exposure has been estimated in the Post-closure Safety Assessment [B-6] and determined to be acceptable in comparison to design criteria (i.e., <0.3 mSv/a) and public dose limits (i.e., < 1 mSv/a) for all plausible scenarios.

Potential consequences resulting from accidents, such as fire, have been estimated in the Safety Analysis Report [B-7]. To confirm that the analysis radionuclides dominating potential exposure, radionuclide significance in the context of contributing to internal radiation dose was assessed by multiplying radionuclide activity for all radionuclides present in CNL's waste database and corresponding dose coefficients for ingestion and inhalation from ICRP 119. While other factors, such as potential for resuspension and dispersion, also contribute to exposure, assuming dispersion has occurred in proportion to the initial inventory, the distribution and relative consequence for the NSDF radionuclide inventory in terms of internal dose is provided in Table B-2. It can be seen that just three radionuclides, Cs-137, Co-60 and Am-241 dominate potential exposure via ingestion and inhalation. Just 0.09% of the total contribution to the ingestion dose is due to radionuclides other than these three and Tritium plus Sr-90, all of which are included in the NSDF Reference Inventory. Although a higher proportion of inhalation dose is due to radionuclides not included in the NSDF inventory, it is still below 10%. Furthermore, the majority of this unaccounted contribution is due to

just one radionuclide – Cm-244. The inventory data for Cm-244, as recorded in CNL's waste database are disproportionately high compared to its progeny (i.e., Pu-240) and are almost certainly unrealistic.

Table B-2
Radionuclide Ranking by Internal Dose Contribution

Nuclides in WIP-III Database	Ranking by Ingestion Dose Contribution, %	Ranking by Inhalation Dose Contribution, %
Cs-137	66.16	34.40
Co-60	33.13	52.36
Am-241	0.07	5.70
Sr-90	0.34	0.34
H-3	0.20	0.22
All other	0.09	6.99

B.1.1.4 Summary

Table B-1 and Table B-2, indicate that even if all radionuclides for which data are available in CNL's waste database were to be considered, just four radionuclides would dominate potential internal and exposure pathways for normal operations. These radionuclides have been identified in all analysis and design calculations for NSDF operations.

B.2 POST-CLOSURE

B.2.1 SCREENING BY HALF-LIFE

As in the case of pre-closure, radionuclides used in the NSDF inventory were limited to isotopes with half-lives over five years (i.e., Table A-2). Given the planning basis of a 300 year period of institutional control [B-5], all short lived radionuclides that are not generated as a result of in-growth from other nuclides, will have decayed prior to the end of the design life of the NSDF engineered features for containment. Limiting the post-closure reference inventory to radionuclides with half-lives over five years is consistent with the best international practice.

B.2.2 BENCHMARKING

As for pre-closure, human and ecological exposure will result from external and internal doses. In that respect analysis presented for pre-closure also applies to post-closure selection. However, in the context of post-closure, other factors become important in addition to radio-toxicity, such as:

- Half-life
- Potential for in-growth of other radionuclides and
- Sorption properties.

A combination of these factors is taken into account in the exposure scenarios, including inadvertent human intrusion and groundwater transport. These same scenarios, which are significant in the context of NSDF post-closure have been considered in post-closure safety assessment studies for other similar facilities. Significant radionuclides have been identified in the following references:

- Performance Assessment for the Idaho CERCLA Disposal Facility Landfill [B-8].
- Low Level Waste Repository (LLRW) Environmental Safety Case, UK [B-9].
- Post-closure Safety Assessment for Ontario Power Generations Deep Geologic Repository [B-10].

The first two of these studies considered NSDFs for operational facilities. The latter, considered a deep repository and is less applicable to NSDF but is included for comparison to a Canadian disposal facility.

The results of benchmarking are provided in Table B-3. The table illustrates that the list of radionuclides included in the NSDF captures all radionuclides identified as significant under recent post-closure safety assessment for selected disposal facilities. The Idaho CERCLA Performance Assessment, in particular, is directly applicable because:

- Similar waste streams were considered, which included arisings from operation and decommissioning of a nuclear laboratory.
- The same waste forms are present at the Idaho CERCLA landfill, such as solid debris, activated metals, soils, concrete, glass, steel, wood, metals, plastic, grout, piping, filters, Personal Protective Equipment, etc.
- Radionuclide screening included a two-step approach (by half-life and using GWSCREEN model), which is applicable to NSDF pathways.

Table B-3
Benchmarking of Significant Radionuclides

Radionuclide	**Idaho CERCLA, US [B-8]**	**LLWR, UK [B-9][(a)]**	**DGR, Canada [B-10][(b)]**	**NSDF**
Ag-108m	-	✓	✓	✓
Am-241	-	✓	✓	✓
Am-243	-	✓	✓	✓
C-14	✓	✓	✓	✓
Cl-36	✓	✓	✓	✓
Co-60	-	✓	-	✓
Cs-135	-	✓	-	✓
Cs-137	-	✓	✓	✓
H-3	✓	✓	✓	✓
I-129	✓	✓	✓	✓
Mo-93	-	✓	✓	✓
Nb-94	-	✓	✓	✓
Ni-59	-	-	✓	✓
Ni-63	-	✓	✓	✓
Np-237	✓	✓	✓	✓

Radionuclide	**Idaho CERCLA, US [B-8]**	**LLWR, UK [B-9][(a)]**	**DGR, Canada [B-10][(b)]**	**NSDF**
Pu-239	✓	✓	✓	✓
Pu-240	✓	✓	✓	✓[(c)]
Pu-241	-	✓	✓	✓
Pu-242	-	✓	✓	✓
Ra-226	-	✓	✓	✓
Se-79	-	-	✓	✓
Sn-126	-	-	-	✓
Sr-90	-	✓	✓	✓
Tc-99	✓	✓	✓	✓
Th-230	-	✓	-	✓
Th-232	-	✓	-	✓
U-233	✓	✓	✓	✓
U-234	✓	✓	✓	✓
U-235	✓	✓	✓	✓
U-238	✓	✓	✓	✓
Zr-93	-	✓	✓	✓

Note a: The Low Level Radioactive Waste Facility list of retained radionuclides also includes: Ca-41, Nb-93m, Pb-210, Ra-228, Ac-227, Th-228, Th-229, Pa-231, U-236, Pu-238, Pu-244, Am-242m, Cm-243, Cm-243, Cm-244, Cm-245, Cm-246, and Cm-248.

Note b: The OPG DRG list of Potentially Important Radionuclides also includes: Nb-93m, Sn-121m, Ir-192m, Pt-193, Pb-210, U-232, U-236, Pu-238, Am-242m, Cm-243 and Cm-244

Note c: For the NSDF Reference Inventory Pu-240 are reported as Pu-239/240 as these radionuclides are generally combined in laboratory analysis.

B.3 SUMMARY

Post-closure analysis for NSDF used a select set of radionuclides, which was consistent with pre-closure. A number of additional factors, such as in-growth and sorption, impact selection of radionuclides contributing to exposure. Table B-3 confirms that NSDF inventory considered all 11 radionuclides which were screened in for the Idaho CERCLA facility by evaluating relative significance of factors specific to post-closure. Radionuclides which were found to dominate long-term exposure for UK's LLWR and proposed Deep Geological Repositories in Canada are also considered.

B.4 CONCLUSION

Comparative analysis of doses from individual radionuclides and benchmarking confirmed that the list of radionuclides selected for NSDF includes those that dominate worker and public exposure in the context of pre- and post-closure. Therefore, the NSDF radionuclide list used in the following documents is adequate:

- Post-Closure Safety Assessment
- Environmental Impact Statement
- Safety Analysis Report
- NSDF design documentation

B.5 REFERENCES

[B-1] *Radionuclides of Concern NSDF: Verification of Radionuclide Screening*, 232-503230-021-000-0018, Revision 0, 23311119.

[B-2] *Compendium of Dose Coefficients Based on ICRP Publication 60,* ICRP Publication 119, International Commission on Radiation Protection, 2012.

[B-3] *Nuclear Decay Data for Dosimetric Calculations*, ICRP Publication 107, International Commission on Radiation Protection, 2008.

[B-4] *Human Intrusion Model for the Fourth and Fifth Case Studies: HIMv2.0,* NWMO TR-2012-04, Nuclear Waste Management Organization.

[B-5] *Performance Assessment for Near Surface Disposal Facility – 100% Design*, 232-509240-ASD-001, Revision 1, 22678306.

[B-6] *Post-Closure Safety Assessment 3rd Iteration to the NSDF Project,* 232-509240-ASD-004, Revision 0, 50013064.

[B-7] *NSDF Safety Analysis Report,* 232-508770-SAR-002, Revision 0, 48120559.

[B-8] *Performance Assessment for the Idaho CERCLA Disposal Facility Landfill*, DOE/ID-10978 Revision 2, Idaho National Laboratory.

[B-9] *The 2011 Environmental Safety Case: Assessment of Long-term Radiological Impacts,* LLWR/ESC/R(11)10028, LLW Repository Ltd.

[B-10] *OPG's* Deep Geologic Repository for Low and Intermediate Level Waste, *Post-closure Safety Assessmen*t, NWMO DGR-TR-2011-25, Nuclear Waste Management Organization.

APPENDIX C PACKAGED WASTE

C.1 EXTRACTION OF CNL'S WASTE DATABASE

The data used for the packaged waste inventory was extracted from CNL's radioactive waste inventory program called Waste Inventory Program, version 3 (WIP III). The following steps were taken to extract the data from WIP-III.

1. A contaminant query (*? Contams*) was run with each radionuclide on the list that was supplied by the NSDF group as a radionuclide of concern for long term safety (*using the drop down menu*).
2. As data was required to be in becquerels or in grams, packages that did not have measured data were excluded, to do this, the "*Suspect*" column was set to "*N*".
3. After obtaining results, a package query (*Get Pkgs)* was run to get packages associated with the chosen nuclide.
4. The results were saved as a Comma-Separated Values table (.CSV) (*save current window to file, each window saved individually).*
5. The two results (package and contaminant) were combined into same spreadsheet and converted to Excel.
6. These steps were repeated for each radionuclide of concern.

Next, the files were modified to combine data from two sheets and to remove some data that is not necessary for this exercise, to save file space, as the files were quite large.

In the radionuclide Excel file, on the package sheet:

1. To keep the inventory constant, packages after Dec 31 2015 were removed (work initially done in 2016 January).
2. Duplicate packages were removed using the "Remove duplicates" option in Excel (when a package is moved in WIP-III, a copy is generated).
3. Spent Fuel (34000/3H000, 44000/4H000 & some 54000 (not the cemented molybdenum waste); BML & WMA C, waste were removed from inventory.
4. Waste that labelled as "Safeguard" was removed.
5. Post processing packages (e.g., compactor bins, bales from Waste Treatment Centre) were removed to ensure no double counting package content.
6. Certain columns that were not necessary to generate the inventory were removed to save file space. This includes the columns with the headers: X; Y; Z; received_date (duplicate); pkg_comment; pss_id; supporting_doc_num; data_entered_name; data_entered_date; overpack_id; transfer_num; moved_date; processed_flag; physical_state; sug_disposition_storage; sug_disposition_disposal; sug_disposition_processing; accountable_qty; packages_inspected; result_of_processing; processed_content.
7. Volumes of Shielded Modular Above Ground Storage (SMAGS) packages were adjusted to represent the end state volume, based on Radioactive Waste Cost Model [C-2]: Waste to the compactor multiplied by 0.267; Mopheads to bales to read bale bin multiplied by 0.563; drums to SMAGS multiplied by 1.708; Waste to Waste Reception Centre multiplied by 1.308.

In the file, contaminant sheet:

1. To save file space, the contaminant type and suspect columns were removed.
2. If the contaminant was reported in grams, it was converted to Bq using the radionuclide's specific activity.
3. The package mass, package volume and waste material were added to contaminant sheet using Excel's "VLOOKUP" formula, with the Package ID as link between the two sheets.
4. The package activity was calculated (in Bq/g) for each package using the package activity in Becquerels and the package's reported mass (in kilograms).

Analysis of the data from WIP-III revealed that occasionally, on the same waste data sheet, the quantity of Uranium was recorded as Nat-U, Dep-U and Enr-U as well as being reported as U-234, U-235 and/or U-238. Because of this, the following steps were taken:

1. The data reported and Natural U and Depleted U were split into U 234, 235 & 238 based on https://www.wise-uranium.org/rup.html (see Table C-1 below).

Table C-1
Isotopic Activity of Natural and Depleted Uranium

Element	U-234 Activity %	U-235 Activity %	U-238 Activity %
Natural Uranium	48.9%	2.2%	48.9%
Depleted Uranium (by-product of enrichment to 3.5% U-235	14.2%	1.1%	84.7%

2. For Enr-U, enrichment levels were not available from the datasheet, therefore they need to be estimated. This was possible because of the duplicate reporting. The reported quantity of U-235 was compared with the reported quantity of Enr-U for the same package.
3. If there was not duplicate reporting, an enrichment level of 20% was assumed.
4. U-234 was estimated based on a formula that gives the activity ratio [C-1].

$$\text{U-234/U-235 Activity Ratio} = 22.012 + 9.372\ (\log \text{wt\% U-235}) - 3.516\ (\log \text{wt\% U-235})^2$$

5. The result was multiplied by the U-235 activity (calculated).
6. The U-234 mass ratio was then calculated using the specific activity, package mass and Enr-U mass.
7. The U-238 mass ratio was determined as the balance of the U-235 and U-234 mass ratio.
8. The U-238 activity was then calculated using its specific activity.
9. The activities from Nat, Dep and Enr-U were combined onto the same sheet.
10. Activity from Nat, Dep and Enr-U added to the respective U-234, U-235 and U-238 files. Duplicate packages were then removed.

C.2 SCREENING PACKAGES THROUGH THE NSDF WAC

The packages were then sorted into the NSDF WAC, using the sum of fractions rule.

1. The activity (Bq/g) and package ID from each nuclide files were extracted and placed on individual tabs within a new spreadsheet.
2. A list of all the packaged waste was created by combining all the packaged waste and removing duplicates.
3. The activity of each package was combined onto the same sheet, using "VLOOKUP"
4. The values were summed, as Alpha, Long Lived Beta/Gamma, Tritium, Cs-137 and Sr-90 and other short lived beta/gamma.
5. The results were then compared with the WAC.
6. All packages were then sorted into Bulk, Packaged, Stabilized or Exceeds WAC Category

   Note: The Stabilized Category of waste has since been removed from the Reference Inventory; however this work was completed prior to that change.
7. The package ID and WAC Sort result were then extracted and returned to the individual nuclide files.
8. The result added to contams page, using "VLOOKUP".
9. A pivot table was created that shows # of packages, mass, volume and total activity with each category.

These results were then placed on a new spreadsheet, as the base inventory [C-3].

The process above, identified the volume of waste that contained each specific nuclide, however, it did not provide a volume of the waste in the inventory that had contaminant data recorded, nor the volume of packages that only had nuclide outside of those of concern. To get this information, which was used as the baseline volume, the following steps were taken:

1. All packages in WIP-III extracted into Modular Above-Ground Storage/ SMAGS, Bunkers and Tile Holes.
2. Identified if contaminants were associated (could have been characterized, but outside of the significant radionuclides.
3. Duplicates removed.
4. All forms of fuel removed.
5. All long-lived disused sources (greater than five years) were removed from the inventory (assumption is that disused sources will only be accepted on a case-by-case basis).
6. Volumes of SMAGS packages were adjusted to represent the end state volume, based on Radioactive Waste Cost Model, [C-2] (as above).
7. Packages that were the result of processing (e.g. Compactor Bins, Bales) were excluded as nuclides are most often found on the pre-processing packages.
8. The packages were sorted into the WAC Table 6.1 packaging categories (Types 1-4 and Type 6 Bulk and Type 5 Packages).
9. If a package was not found in the WAC sort, it was assumed to be Bulk as the higher radioactivity packages had their radioactivity reported.

These results were then added to the based inventory file [C-3].

C.3 EXTRAPOLATION OF PACKAGED WASTE

The base inventory was extrapolated to the estimated volume of waste in packages of 119 753 m^3 as found in NSDF Waste Forecast Analysis (Table 5) [C-4]. The total volume in this report was only 836 620 m^3; however it did not include the volume projections of WMA F (i.e., 60 500 m^3) and Cemented Stored Liquid Waste (i.e., 260 m^3), which were added to increase the total to 897 380 m^3. This volume was linearly extrapolated to 1 000 000 m^3, increasing the package waste fraction to 133 447 m^3.

As mentioned in Section C.1, not all waste in the WIP-III inventory has contaminant listed with the packages. Most of this waste was listed with "Suspect" contamination, therefore it was assumed that this waste is of lower activity, and has a similar profile as the non-leachate controlled packaged waste.

As such, the base inventory was extrapolated to 133 447 m^3 as described in Table C-2.

Table C-2
Estimated Package Volume in Final Mound by WAC Category

	Non-Leachate Controlled Packaged Waste	Leachate Controlled Packaged Waste
Base Inventory of acceptable packaged	8 686 m^3	1 227 m^3
Base Inventory of acceptable packaged plus packages without radionuclide information were placed in Bulk WAC Category	14 385 m^3	1 227 m^3
Ratio	92.1%	7.9%
Estimated Package Volume in final mound	122 957 m^3	10 490 m^3
Multiplier (Final Volume in mound divided by the Base Inventory)	14.16	8.55

The Base Inventory total radionuclides and mass were multiplied using the same ratio for Packaged Waste that sorted into the Type 5 waste categories.

C.4 DECAY CALCULATIONS

The following appendix sections clarify the steps taken to estimate the Reference Inventory at time of closure. Decay calculations were done using half-lives from the International Commission on Radiation Protection (ICRP) Publication 107 [C-5], as listed in Table C-3.

Table C-3
Half-Lives of NSDF Significant Radionuclides from International Commission on Radiation Protection Publication 107

Radionuclide	Half-Life from ICRP-107 [C-5]
Ag-108m	418 years
Am-241	432.2E+02 years
Am-243	7.37E+03 years
C-14	5.70E+03 years
Cl-36	3.01E+05 years
Co-60	5.2713 years

Radionuclide	Half-Life from ICRP-107 [C-5]
Cs-135	2.3E+06 years
Cs-137	30.1671 years
H-3	12.32 years
I-129	1.57E+07 years
Mo-93	4.0E+03 years
Nb-94	2.03E+04 years
Ni-59	1.01E+05 years
Ni-63	100.1 years
Np-237	2.144E+06 years
Pu-239	2.411E+04 years
Pu-241	14.35 years
Pu-242	3.75E+05 years
Ra-226	1600 years
Se-79	2.95E+05 years
Sn-126	2.30E+05 years
Sr-90	28.79 years
Tc-99	2.111E+05 years
Th-230	7.538E+04 years
Th-232	1.405E+10 years
U-233	1.592E+05 years
U-234	2.455E+05 years
U-235	7.04E+08 years
U-238	4.468E+09 years
Zr-93	1.53E+06 years

C.4.1 PACKAGED WASTE DECAY CALCULATIONS

To determine the Packaged Waste Source Term at time of closure, the total activity of each radionuclide was equally divided. This is to assume that waste will be emplaced evenly during the 50 years of operations of the NSDF. The radionuclides in each fiftieth of the inventory were then decayed (using Equation C-1) based on the assumed amount of time the waste would be in the NSDF prior to closure of the last cell (e.g., the first waste emplaced was decayed for 49 years and the last waste emplaced was not decay corrected). The fraction were then added together to get the decay corrected value. Additionally, radionuclide progeny are considered in equilibrium, with the exception of the ingrowth of Am-241 from the decay Pu-241. The ingrowth of Am-241 was calculated using the Bateman equation (Equation C-2). An extract of the decay calculations that can be found in the Reference Inventory spreadsheet [C-3] is provided in Table 13.

Equation C-1

$$N(t) = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

Where:

- $N(t)$ is the quantity that still remains and has not yet decayed after a time (t);

- N_0 is the initial quantity of the substance that will decay;
- $t_{1/2}$ is the half-life of the decaying quantity.

Equation C-2

$$N_D(t) = \frac{\lambda_P}{\lambda_D - \lambda_P} N_{P_0}\left(e^{-\lambda_P t} - e^{-\lambda_D t}\right) + N_{D_0} e^{-\lambda_D t}$$

Where:

- $N_D(t)$ is the quantity of the daughter radionuclide that still remains and has not yet decayed after a time (*t);*
- N_0 is the initial quantity of the substance that will decay for the parent (P) or daughter (D);
- *λ is the decay constant of the decaying quantity (*Equation C-3*)* for the parent (P) or daughter (D);
- *e is the mathematical constant (≈2.718);*

Equation C-3

$$N(t) = N_0 e^{-\lambda t}$$

Where:

- $N(t)$ is the quantity that still remains and has not yet decayed after a time (*t);*
- N_0 is the initial quantity of the substance that will decay;
- *λ is the decay constant of the decaying quantity (*Equation C-3*)*;
- *e is the mathematical constant (≈2.718);*

Table 13
Extract of Decay Calculations for Packaged Waste

Radionuclide	Half-Life from ICRP-107 [C-5] (years)	Total Package Activity (Bq)	Average Annual Emplacement Activity (Bq)	Total Decayed Activity at Time of Closure	Activity (Bq) at Time of Closure				
					1st Emplacement (decayed 49 years)	2nd Emplacement (decayed 48 years)	Etc.	49th Emplacement (decayed 1 years)	50th Emplacement (decayed 0 years)
Ag-108m	418	2.73E+10	5.47E+08	**2.62E+10**	5.04E+08 (a)	5.05E+08	[…]	5.45E+08	5.46E+08
Am-241	432.2E+02	4.80E+10	9.59E+08	**7.90E+10**	1.88E+09 (b)	1.88E+09	[…]	1.05E+09	1.01E+09
Am-243	7.37E+03	4.62E+07	9.24E+05	**4.61E+07**	9.19E+05 (a)	9.20E+05	[…]	9.24E+05	9.24E+05

Note (a): Decayed using Equation C-1.
Note (b): Decayed using Equation C-2 to account for the ingrowth of Pu-241 (half-life of 14.35 years).

C.4.2 BULK WASTE DECAY CALCULATIONS

The radioactivity of parent radionuclides in the bulk waste are decreasing because no additional source material is being added to the non-operating facilities and WMAs that make up most of the source of bulk waste. To estimate the total activity associated with bulk waste, the source term was decayed for 50 years (using Equation C-4), the operating period of NSDF. Radionuclide progeny are considered in equilibrium where applicable, except for the ingrowth of Am-241 from the decay Pu-241. The ingrowth of Am-241 was calculated

using the Bateman equation (Equation C-2). The decay calculations can be found in the Reference Inventory spreadsheet [C-3].

Equation C-4

$$\lambda = \frac{\ln(2)}{t_{1/2}}$$

Where:

- *ln(2) is the natural logarithm of 2 (≈0.693);*
- $t_{1/2}$ is the half-life of the decaying quantity;
- *λ is a positive number called the decay constant of the decaying quantity (*Equation C-3*)*

C.5 REFERENCES

[C-1] T.L. Rucher and M. Johnson Jr., *Calculation of Uranium Isotopic Activity Composition Based on Data from Various Assay Methods,* Science Application International Corporation, available: https://www.lanl.gov/BAER-Conference/BAERCon-43p016.pdf

[C-2] *Radioactive Waste Cost Model*, 185-508600-REPT-009, Revision 1, 22332486.

[C-3] *Data and Calculations Used for NSDF Reference Inventory Revision 2*, 232-508600-038-000, Revision 0, 50464122.

[C-4] *NSDF Waste Forecast Analysis*, 185-508600-REPT-014, Revision 0, 22218174.

[C-5] *Nuclear Decay Data for Dosimetric Calculations*, ICRP Publication 107, International Commission on Radiation Protection, 2008.

APPENDIX D QUALITATIVE ASSESSMENT OF THE NSDF REFERENCE INVENTORY AND THE SCALING FACTORS

A qualitative assessment of the NSDF Reference Inventory was performed to identify:

- The effect of the assumed radionuclide distribution on the WAC to ensure it is appropriate as it relates to expected distribution from fuel-cycle operations. This is to ensure undue bias has not been assigned to a particular radionuclide by the WAC.
- Whether the assumed total radioactivity appropriately and adequately bounds the Post-Closure Safety Assessment [13] and optimizes NSDF capacity for radioactivity and volume. The NSDF capacity could be limited such that the licensed radioactivity would be reached before the design volume is met or materials that satisfy criteria for long term dose consequence are unnecessarily excluded.

Table D-1 and Table D-2, show that the sources of material used in NSDF Reference Inventory are orders of magnitude less than the WAC limits for the radionuclide types and that the limit fractions by radionuclide type are close to the overall sum of fractions which provides confidence that the WAC is balanced and not unduly biased toward a radionuclide type.

Table D-1
Average Emplaced Packaged Waste Activity compared with WAC Limit

	Alpha	Long Lived Beta/Gamma	Co-60 & Pu-241	Cs-137 & Sr-90	H-3
Average Activity	4.66E+00	4.08E+01	1.32E+06	1.49E+02	1.16E+04
Limit	400	10 000	-	10 000	10 000 000
Percent of Limit	1.2%	0.4%	n/a	1.5%	0.1%

Table D-2
Average Emplaced Bulk Waste Activity compared with WAC Limit

	Alpha	Long Lived Beta/Gamma	Short Lived Beta/Gamma	Tritium
Average Activity	5.10E-02	3.66E-01	1.51E+01	1.10E+02
Limit	100	1 000	10 000	100 000
Percent of Limit	0.1%	0.0%	0.2%	0.1%

D.1 CS-137

As a primary fission product in nuclear fuel-cycle waste that is easily detected, Cs-137 is commonly reported with a suitable degree of precision in waste package records. It serves as the key radionuclide for fission product scaling factor determination and is easily detected in both field and laboratory measurements. The Cs-137 magnitude in the NSDF Reference Inventory has some uncertainty due to the representativeness of the data not being reported. What has been observed is the practice of reporting radioactivity based on maximum values rather than a representative value based on distribution analysis which has the effect of overestimating radioactivity but was deemed acceptable conservatism for the preparation of the NSDF Reference Inventory.

The CNL waste database for package radioactivity represents a package's radioactivity at the time of generation and decay is not applied to package radioactivity records. As the records only represent packages generated from 1995 to 2015, the use of the waste database Cs-137 ($t_{½}$ is 30.1 years) radioactivity as a base assumption is conservative as waste packages have been generated for nearly 70 years. The Cs-137 radioactivity in package data was decayed to represent a steady state disposal of waste over the operational period of the NSDF operation.

The conservatism of the Cs-137 data is represented by mainly two factors:

- Un-decayed concentrations were used to represent the entire packaged waste radioactivity where a portion of the packages would have undergone significant decay.
- The practice of determining a package's radioactivity by "hot spot" or maximum activity detected.

This conservatism is transferred to the portion of the NSDF Reference Inventory assigned to packaged waste. The uncertainty associated with the Cs-137 concentrations in packaged waste is influenced by this conservatism, but cannot be quantified at this time.

Concentrations of Cs-137 are more current in environmental remediation and decommissioning forecast data and used directly to inform their portion of the NSDF Reference Inventory. Generally, the Cs-137 concentration in the NSDF Reference Inventory is considered to be conservative, as the practice of estimating radioactivity by "hot spot" has been commonly used. Industry standard approach to waste characterization will be used to address the specific topics of representativeness, precision and accuracy in waste being characterized for NSDF disposal.

D.2 AM-241

Americium-241 is the long lived alpha emitting daughter of the beta emitting Pu-241 (half-life of 14.3 years). This actinide is often used to identify other hard to measure actinides, its scaling factor applied to gamma spectroscopy results where limited sample analysis was performed. Decay was not undertaken by CNL waste database; therefore the in-growth of the daughter product Am-241 from Pu-241 is under reported in the data and Pu-241 is over reported in the data.

Affected land areas on the CNL site have been sampled in various campaigns throughout the operational periods of the sites. This data was used to estimate the impact of their radioactivity on the environment and in these sample data, Am-241 has been detected as are several additional radionuclides quantified by more complete analysis. As in the packaged waste, this data were decayed to 2017 July, to adjust for Pu-241 decay and the in-growth of Am-241.

D.3 URANIUM

Uranium concentrations in stored package data were reported in an array of conventions where each of the radionuclides and/or Natural Uranium (NAT-U), Depleted Uranium (DEP-U) and Enriched Uranium (ENR-U) or a combination of both was observed. An effort was made to eliminate duplications and separate the Uranium concentrations into a single value for each of the Uranium radionuclides. Uranium concentration for decommissioning and environmental remediation waste streams was scaled-in due to limited characterization of all areas.

Site criticality safety documents indicate that fissionable material, present in affected land areas, was deposited by flowing dissolved ions and fine suspended solids onto a cobble weir system designed to limit the

mobility of the material. In addition, the process liquid was associated with reactor operations using varied fuel enrichment. As a result, a conservative inventory for these areas was assumed where all fissionable material deposited is accounted for as either Pu-239, U-233 or U-235. The same conservatism was likely used to assume the same conditions exist for reported Uranium concentrations in waste packages being stored at WMA-B. In general, the average distribution of the Uranium radionuclide concentrations represented in the data closely follows NAT-U/DEP-U distribution, characterization will be assessed for waste acceptance.

Table D-3
NSDF Uranium Mass by Waste Type

Radionuclide	Packaged Waste (g)	Bulk Waste (g)	Total Emplaced (g)
U-233	6.71E-01	9.18E-02	7.63E-01
U-234	2.56E+02	4.03E+01	2.97E+02
U-235	3.21E+04	4.88E+03	3.70E+04
U-238	5.39E+06	6.85E+05	6.08E+06
		Total (g)	**6.12E+06**

Table D-4
NSDF Plutonium Mass by Waste Type

Radionuclide	Packaged Waste (g)	Bulk Waste (g)	Total Emplaced (g)
Pu-239	3.36E+01	4.47E+00	3.80E+01
Pu-241	3.83E-01	5.29E-02	4.36E-01
		Total (g)	**3.85E+01**

D.4 OTHER ACTINIDES

Actinide concentrations in waste, have significant impact on long-term dose consequence and are present in CNL waste streams that originate from fuel-cycle operations. Concentrations in stored package data are inconsistently reported, most likely due to the varied approaches used for characterizing waste. It has been observed that other actinide radioactivity for the higher total activity packages has been reported in CNL's waste database data more consistently, and have a weighting effect on the data. The source data in CNL's waste database represents packaged radioactivity at time of generation and no decay of radionuclides is/was performed. As a result, the inventory was adjusted to account for the in-growth of Am-241 (see above, D.2).

As a part of environmental remediation planning, historic sample data was analyzed to assess the uniformity of Uranium, Americium and Plutonium distributions in various affected land areas of the site. This analysis included samples from the affected land areas on the CRL site. Scaling factors were produced, which could be useful in the larger characterization effort required for these areas. This condition may also exist for the other CNL sites like the Whiteshell Laboratories and further investigation will provide more detail regarding the condition.

When the observed Am-241: Cs-137 ratios are plotted (Figure D-1), the data indicate that the radionuclide distribution is fairly consistent across all the affected lands. As indicative evidence of this condition, the plot below provides a derivation of the Am-241: Cs-137 scaling factor.

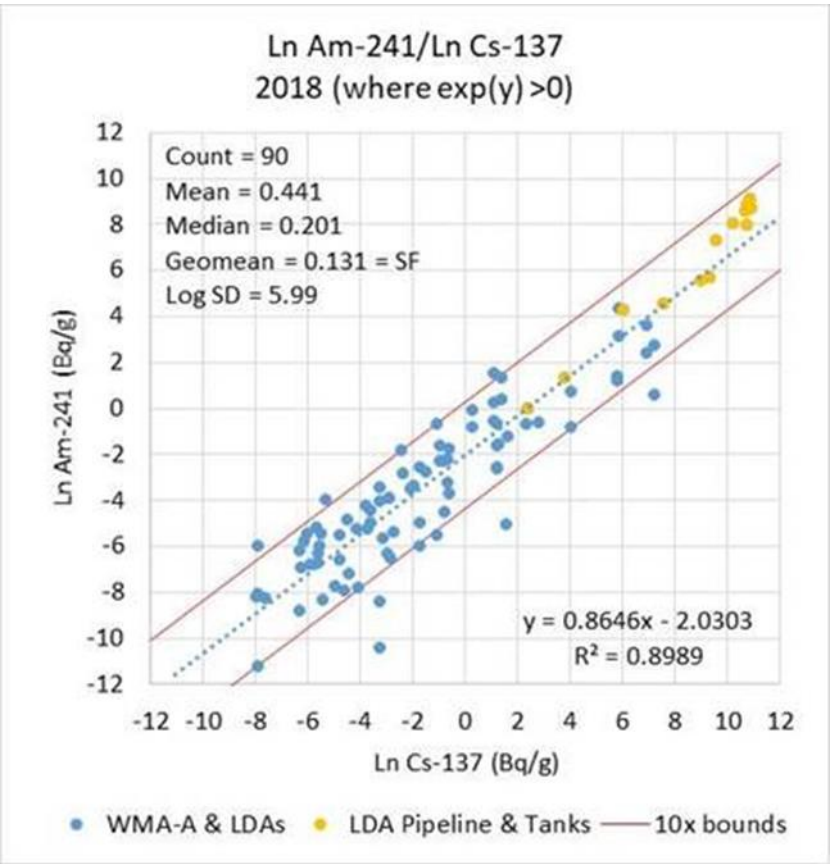

Figure D-1 Am-241/Cs-137 Ratios (Scaling Factors)

The plotted Am-241: Cs-137 ratios, lend confidence to the notion that the affected lands are contaminated with the same materials as the observed scaling factors for Am-241:Cs-137 are reasonably bounded by a factor of ±10. Depending upon the variability of the data, separate plots may be developed. Ideally, in this type of scaling factor plot, the slope should approximate 1 because the ratio should not markedly change with increases in activity concentration. However, in Figure D-1, the untransformed data on the x and y axis span 10 orders of magnitude such that a slope of 0.86 is not considered a significant deviation from a slope of 1. In general this effort has identified Am-241: Cs-137 ratios range from approximately 5% to 15%. While this relationship would not normally be used when Am-241 is detected, it can be used as a secondary relationship when Am-241 is not detected in the presence of Cs-137 to scale in other actinides.

A word of caution when using Am-241 for a key radionuclide for actinides, is that it must be largely built in (decay corrected) from its parent T½ 14.4 a Pu-241 prior to use. The data in Figure D-2 is all from wastes >50 years old. Correlations have been observed in the Pu-239: Am-241 relationship in environmental remediation soils and the same would be expected to be observed in fuel-cycle wastes generated during the same time period. The plotted sample data is shown below in Figure D-2.

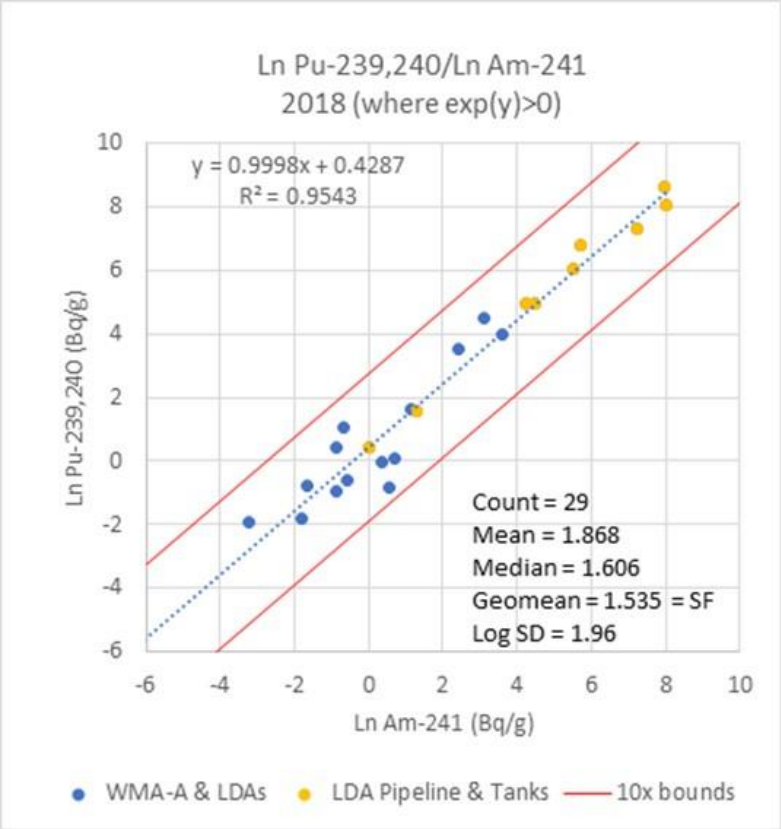

Figure D-2 Pu-239/Cs-137 Ratios (Scaling Factors)

Figure D-2 depicts an excellent fit with a natural slope of 1 and in this instance, the untransformed data only spans 4 decades such that a slope closer to 1 is desirable as compared to Figure D-1.

D.5 FISSION PRODUCTS

The full range of radionuclides produced by the nuclear fuel-cycle are present in most CNL wastes but as the Reference Inventory is focused on post-closure dose consequence, some radionuclides are not included if they have short half-life, low dose coefficient or low abundance or any combination of these factors that limit their impact on long term dose consequence. Examples of fission product radionuclides that are present in CNL waste streams but not reported in the Reference Inventory are: Eu-154, Ru/Rh-106, and Ce-144.

During the development of the Reference Inventory, it was noted that Zr-93, I-129 and Cs-135 were present in quantities that far exceeded their production potential. Adjustments were made to these values based on the mean ratios modeled in site specific 80% burn-up National Research Universal fuel assemblies using ORIGEN.

D.6 ACTIVATION PRODUCTS

As with the fission products, the full complement of radionuclides reasonably expected to be present in CNL waste streams, will be identified in characterization efforts but only those significant to post-closure dose consequence are of interest to the Post-closure Safety Assessment and thusly, to the NSDF Reference Inventory. As with the fission products, some activation product radionuclides that are present in the waste (Fe-55, Mn-54, Cr-51 and Zn-65 as examples), are not evaluated for the same reason. Included in

investigations of environmental remediation samples is an examination of the Cs-137: Co-60 ratios. This is helpful to characterization as it can assist with quantifying longer lived hard-to-measure activated corrosion products such as Ni-63 and Mo-93 in cases where the shorter lived Co-60 may not be detected but the longer lived Cs-137 can be detected. This is another example of using Cs-137 as a secondary key radionuclide when the preferred radionuclide (Co-60) is not detected and long lived activation products are known to be present. To provide this observation, the Cs-137: Co-60 ratios in the data are plotted below in Figure D-3.

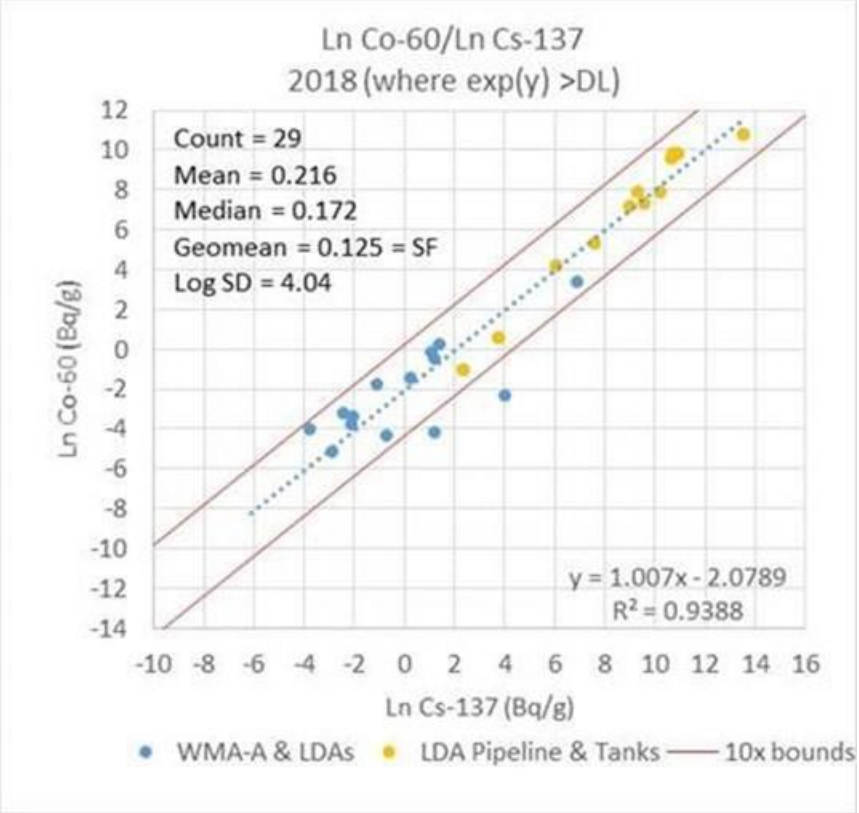

Figure D-3 Cs-137/Co-60 Ratios (Scaling Factors)

While the scatter in Figure D-3 is somewhat greater than that of Figure D-2, a slope of 1 is attained over an untransformed range of 8 orders of magnitude.

APPENDIX E EVALUATION OF DECOMMISSIONING AND ENVIRONMENTAL REMEDIATION PROJECTS

E.1 EVALUATION OF THE DECOMMISSIONING WASTE RADIONUCLIDE INVENTORY

Since the development of the Reference Inventory, additional characterization has occurred at Chalk River and at Whiteshell Laboratories on decommissioning projects. The recent data from Whiteshell B411 [E-1] and Chalk River B102, is compared with the estimated Source Term of Bulk Waste.

E.1.1 WHITESHELL BUILDING 411

Building 411 Decontamination Centre, provided a decontamination service for maintaining research and development experimental rigs, equipment and tools, as well as a laundry service for radioactively contaminated clothing. The 850 m² building was located in the Controlled Area 2 at Whiteshell Laboratories. Whiteshell Building 411 was turned over for decommissioning on 2016 January and successfully demolished in 2017 September [E-1]. A summary of the radiological characterization data for Whiteshell B411 is presented in Table E-1.

Table E-1
Radionuclide Data from Whiteshell Building 411

Radionuclide	Activity Concentration (Bq/g)	Total Activity (Bq) in 2.50E+08 g of Waste
Am-241	2.05E-01	5.12E+07
Cm-244	2.46E-03	6.15E+05
Co-60	6.65E-03	1.66E+06
Cs-137	8.90E+00	2.23E+09
Eu-154	1.63E-02	4.08E+06
Nb-94	4.82E-02	1.20E+07
Pu-238	5.59E-02	1.40E+07
Pu-239/240	2.35E-01	5.88E+07
Pu-241	4.38E-01	1.10E+08
Sr-90	5.14E+00	1.28E+09

E.1.2 CHALK RIVER BUILDING 102

Building 102 was a brick building with a steel frame constructed in 1945 and served multiples purposes, notably; Heavy Water Re-concentration, Heavy Water drum cleaning and large equipment decontamination [E-2] and [E-3]. Building 102 was demolished in 2018 and the radionuclide data of waste that meets the proposed NSDF WAC for Bulk is presented in Table E-2, Table E-3 and Table E-4.

Table E-2
Radionuclide Data from Building 102 Brick Debris

Radionuclide	Activity Concentration (Bq/g)	Total Activity (Bq) in 1.29E+08 g of Waste
Am-241	2.34E-02	3.02E+06
Co-60	4.58E-02	5.91E+06
Cs-137	2.19E-01	2.83E+07
Eu-154	4.80E-02	6.20E+06
Eu-155	4.58E-02	5.91E+06
H-3	1.30E+01	1.68E+09
Nb-94	5.48E-03	7.07E+05
Nb-95	1.56E-02	2.01E+06
Pu-238	1.30E-01	1.68E+07
Pu-239/240	7.19E-02	9.28E+06
Sr-90	5.13E-01	6.62E+07
Th-228	1.91E+00	2.47E+08
Th-230	1.88E+00	2.43E+08
Th-232	1.38E+00	1.78E+08
Th-234	3.25E+00	4.20E+08
U-233/240	2.42E+00	3.12E+08
U-235	3.56E-01	4.60E+07
U-238	3.25E+00	4.20E+08

Table E-3
Radionuclide Data from Building 102 Equipment

Radionuclide	Activity Concentration (Bq/g)	Total Activity (Bq) in 1.41E+06 g of Waste
Ag-108	2.66E-01	3.75E+05
Am-241	4.69E-01	6.61E+05
C-14	7.78E+00	1.10E+07
Cm-243	1.27E-01	1.79E+05
Co-60	1.37E+00	1.94E+06
Cs-137	2.12E+00	2.99E+06
Eu-154	1.00E+00	1.42E+06
Eu-155	1.78E-01	2.51E+05
H-3	2.10E+01	2.97E+07
Nb-94	3.01E-01	4.24E+05
Pu-238	2.14E-01	3.02E+05
Pu-239	3.01E-02	4.24E+04
Pu-240	3.87E-01	5.45E+05
Pu-241	1.89E+01	2.67E+07
Sr-90	1.64E+01	2.31E+07
Th-229	3.01E-01	4.24E+05

Table E-4
Radionuclide Data from Building 102 Structural Steel

Radionuclide	Activity Concentration (Bq/g)	Total Activity (Bq) in 8.23E+06 g of Waste
Am-241	2.34E-02	1.92E+05
Co-60	4.58E-02	3.77E+05
Co-60	4.58E-02	3.77E+05
Cs-137	2.19E-01	1.80E+06
Eu-154	3.80E-02	3.13E+05
Eu-155	4.58E-02	3.77E+05
H-3	1.30E+01	1.07E+08
Nb-94	5.48E-03	4.51E+04
Nb-95	1.56E-02	1.28E+05
Pu-238	1.30E-01	1.07E+06
Pu-239/240	7.19E-02	5.92E+05
Ra-226	1.45E-02	1.19E+05
Ra-228	1.52E+00	1.25E+07
Sr-90	5.13E-01	4.22E+06
Th-228	1.91E+00	1.58E+07
Th-230	1.88E+00	1.54E+07
Th-232	1.38E+00	1.13E+07
Th-234	3.25E+00	2.68E+07
U-233/234	2.42E+00	1.99E+07
U-235	3.56E-01	2.93E+06
U-238	3.25E+00	2.68E+07

E.2 EVALUATION OF THE ENVIRONMENTAL REMEDIATION WASTE RADIONUCLIDE INVENTORY

Since the development of the Reference Inventory, additional intrusive characterization has occurred at Chalk River and at Whiteshell Laboratories. The recent data from WMA A [E-2], Liquid Dispersal Areas [E-3], the Cesium Pond [E-4], and WMA F [E-5] is compared with the estimated source term of environmental remediation waste.

E.2.1 WASTE MANAGEMENT AREA A

Waste Management Area A is a non-operating radioactive waste storage facility located at the CRL site. Although records for WMA A are limited, emplacements to the area are known to include contaminated soil, contaminated equipment and parts, fuel rod ends, general refuse, and large-scale dispersal of contaminated water following the National Research Experimental Reactor accident. Forty-five boreholes were drilled and 19 groundwater monitoring well were sampled, and a summary of the results of the dominant radionuclides are presented in Table E-5 [E-4].

Table E-5
Waste Management Area A Intrusive Sampling Summary

	Am-241	Cs-137	Co-60	Sr-90
Geometric mean (Bq/g)	1.23E-01	2.23E-01	3.45E-03	3.36E-01
Estimated total activity (Bq) in 43 000 m^3 with a density of 1600 kg/m^3.	8.46E+09	1.53E+10	2.37E+08	2.31E+10

E.2.2 LIQUID DISPERSAL AREAS

The LDA was historically used for the dispersal of Low-Level Radioactive Liquid Wastes from 1953 to 2000. Three categories of active liquid wastes were segregated into separate dispersal pits: (1) Reactor Waste, (2) Laundry and Decontamination Waste, and (3) Chemical Waste. A total of 35 boreholes were drilled during the LDA intrusive characterization, including two background holes and five test pits were advanced. A summary of results of the dominant radionuclides are presented are in Table E-6 [E-5].

Table E-6
Liquid Dispersal Area Intrusive Sampling Summary

	Am-241	Cs-137	Co-60	Sr-90
Geometric mean (Bq/g)	3.81E-01	1.34E+00	6.66E-02	1.30E+00
Estimated total activity (Bq) in 58 469 m^3 with a density of 1600 kg/m^3.	3.56E+10	1.25E+11	6.23E+09	1.21E+11

E.2.3 CESIUM POND SOIL PILE CAMPAIGN

As part of Whiteshell Laboratories Closure Project, 2 366 m^3 of soil contaminated with Cs-137 was excavated and shipped to CRL for storage. The soil had been segregated using a soil sorting system which used 61 000 gamma assay measurements in 19 batches to measure the Cs-137 activity. A summary of the results are presented in Table E-7 [E-6].

Table E-7
Cesium Pond Soil Pile Sampling Summary

	Cs-137
Weighted Average (Bq/g)	4.82E+00
Estimated total activity (Bq) in 2 303.71 tonnes [(a)] of soil.	1.11E+10

Note a: the shipped mass was 2.49E+06 kg with a volume of 2 366 m^3.

E.2.4 WASTE MANAGEMENT AREA F

The predicted availability of the proposed NSDF in the near term (<10 years), has advanced the timeline for executing large scale remediation of affected areas of the CRL site. Intrusive characterization was conducted at WMA F to establish if the stored material will meet the specifications of the NSDF WAC [E-8]. Table E-8 provides the results of borehole sampling and laboratory analysis completed from 2018 April to May [E-7].

Table E-8
Waste Management Area F Intrusive Sampling Summary

	Ra-226	Th-230	Th-232	U-234	U-235	U-238
Geometric mean (Bq/g)	4.72E-01	1.28E+00	1.32E-01	9.50E-01	9.28E-02	6.49E-01
Estimated total activity (Bq) in 60 500 m^3 with a density of 1600 kg/m^3.	4.57E+10	1.23E+11	1.27E+10	9.19E+10	8.98E+09	6.28E+10

E.3 REFERENCES

[E-1] *Characterization Results Summary*, *B411 Decontamination Centre*, WL-508600-021-000-0084, Revision 0, 41426783.

[E-2] *Gamma Spectrometry of Four Marine Containers Containing Active Building Material from B102 Located at WMA H*, 213-508600-040-000-0418, Revision 0, 41551331.

[E-3] *Total Activity Consignment for Three Marine Containers Containing Demolition Waste from Building 102*, 213-508600-021-000-1721, Revision 1, 44166723.

[E-4] *Intrusive Characterization at WMA A*, 3611-509410-ASD-015, Revision 0, 40649486.

[E-5] *Intrusive Characterization at the Liquid Dispersal Areas*, 3611-509410-ASD-016, Revision 0, 3611-509410-ASD-016.

[E-6] *Cesium Pond Soil Pile Campaign*, WL-508600-016-000-0002, Revision 0, 16811814.

[E-7] *Intrusive Characterization of Waste Management Area F*, 3611-509410-ASD-017, Revision 0, 48115192.

[E-8] *Waste Acceptance Criteria*, 232-508600-WAC-003, Revision 0, 50398127.