Radionuclide inventory for application of extension of the SFR repository - Treatment of uncertainties

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

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Innehåll

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved   3 (23)

1   Introduction

The reference radionuclide inventory is presented in the reference inventory report (SKB 2013, Mo-93 has thereafter been updated, see section 2.1), where several different methods for estimating the activity of the most important radionuclides in the SFR inventory have been applied depending on the type and origin of the waste. Each method is associated with an uncertainty. This report therefore presents a reference inventory and an estimated maximum inventory which would be valid if the considered uncertainties are evaluated at a confidence level of 95%. The waste packages are assumed to be placed in the waste vaults according to the deposition strategy presented in Gordon (2014).

Figure 1-1 illustrates how the methods for estimation differ depending on the type and origin of the waste. In addition to the uncertainties associated with the methods for estimation, there are also uncertainties coupled to the future waste production, e.g. the amount of waste packages that will be disposed of in SFR before closure. These uncertainties have, however, not been considered in the calculations in this report.
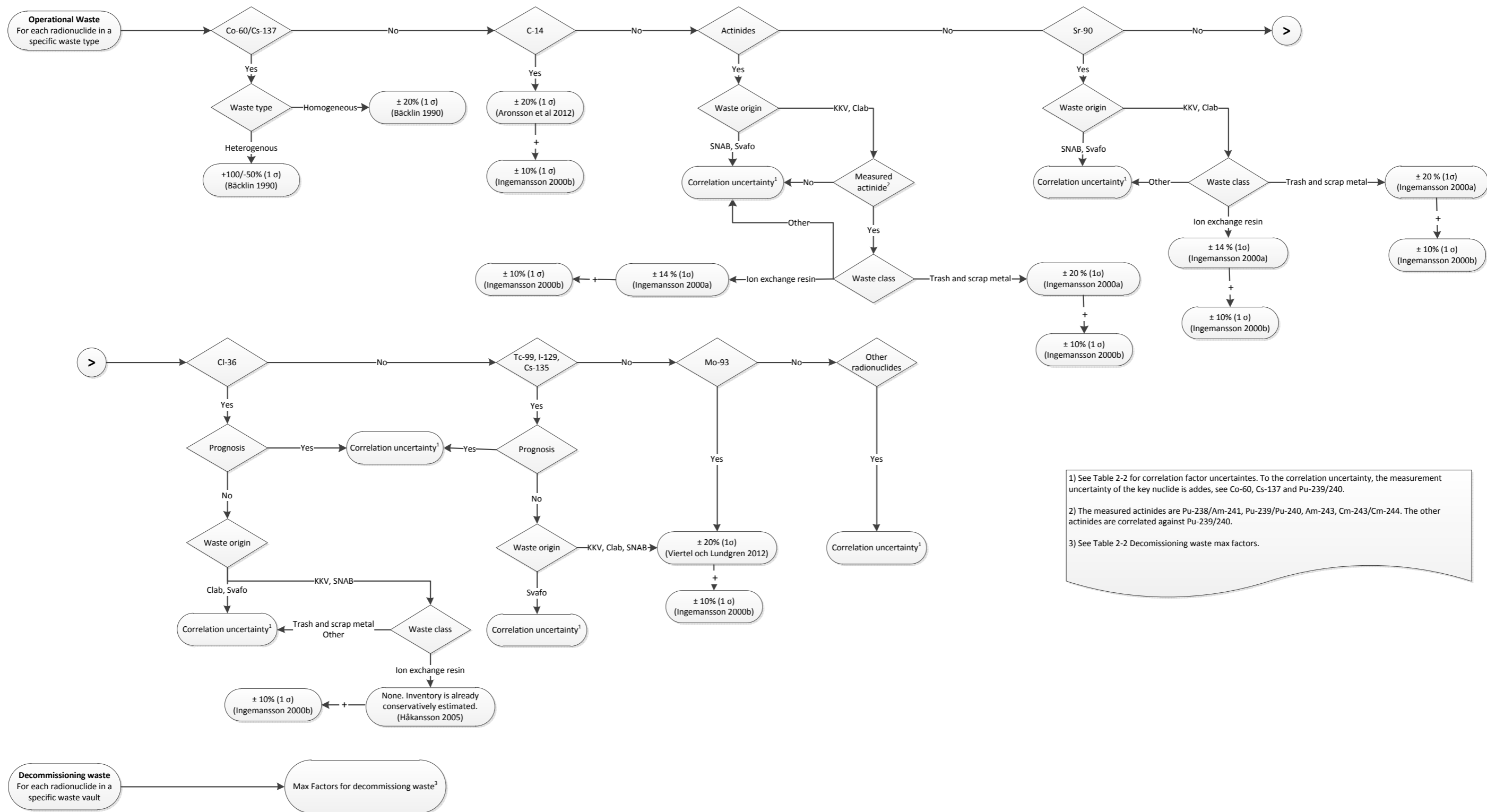
Operational Waste
For each radionuclide in a specific waste type

Co-60/Cs-137 —No→ C-14 —No→ Actinides —No→ Sr-90 —No→ >

Co-60/Cs-137 — Yes
Waste type — Homogeneous → ± 20% (1 σ) (Bäcklin 1990)
Waste type — Heterogenous → +100/-50% (1 σ) (Bäcklin 1990)

C-14 — Yes → ± 20% (1 σ) (Aronsson et al 2012)
+
± 10% (1 σ) (Ingemansson 2000b)

Actinides — Yes
Waste origin — KKV, Clab
Waste origin — SNAB, Svafo → Correlation uncertainty[1]
Measured actinide[2] — No → Correlation uncertainty[1]
Measured actinide[2] — Other → Correlation uncertainty[1]
Measured actinide[2] — Yes
Waste class — Ion exchange resin → ± 14 % (1σ) (Ingemansson 2000a) + → ± 10% (1 σ) (Ingemansson 2000b)
Waste class — Trash and scrap metal → ± 20 % (1σ) (Ingemansson 2000a) + → ± 10% (1 σ) (Ingemansson 2000b)

Sr-90 — Yes
Waste origin — KKV, Clab
Waste origin — SNAB, Svafo → Correlation uncertainty[1]
Waste class — Other → Correlation uncertainty[1]
Waste class — Trash and scrap metal → ± 20 % (1σ) (Ingemansson 2000a) + → ± 10% (1 σ) (Ingemansson 2000b)
Waste class — Ion exchange resin → ± 14 % (1σ) (Ingemansson 2000a) + → ± 10% (1 σ) (Ingemansson 2000b)

> — Cl-36 —No→ Tc-99, I-129, Cs-135 —No→ Mo-93 —No→ Other radionuclides

Cl-36 — Yes
Prognosis — Yes → Correlation uncertainty[1]
Prognosis — No
Waste origin — Clab, Svafo → Correlation uncertainty[1]
Waste origin — KKV, SNAB
Waste class — Trash and scrap metal / Other → Correlation uncertainty[1]
Waste class — Ion exchange resin → None. Inventory is already conservatively estimated. (Håkansson 2005) + → ± 10% (1 σ) (Ingemansson 2000b)

Tc-99, I-129, Cs-135 — Yes
Prognosis — Yes → Correlation uncertainty[1]
Prognosis — No
Waste origin — KKV, Clab, SNAB → ± 20% (1σ) (Viertel och Lundgren 2012) + → ± 10% (1 σ) (Ingemansson 2000b)
Waste origin — Svafo → Correlation uncertainty[1]

Mo-93 — Yes → ± 20% (1σ) (Viertel och Lundgren 2012) + → ± 10% (1 σ) (Ingemansson 2000b)

Other radionuclides — Yes → Correlation uncertainty[1]

1) See Table 2-2 for correlation factor uncertaintes. To the correlation uncertainty, the measurement uncertainty of the key nuclide is addes, see Co-60, Cs-137 and Pu-239/240.

2) The measured actinides are Pu-238/Am-241, Pu-239/Pu-240, Am-243, Cm-243/Cm-244. The other actinides are correlated against Pu-239/240.

3) See Table 2-2 Decomissioning waste max factors.

Decommissioning waste
For each radionuclide in a specific waste vault → Max Factors for decommissioing waste[3]

Figure 1-1 Radionuclide uncertainty flow sheet. KKV means the nuclear power plants

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2   Methodology

2.1   Reference inventory for Mo-93

The reference inventory for Mo-93 has been updated since the reference inventory report was published (SKB 2013). The update was made due to a change in the calculation model for this nuclide in operational waste, which had a major impact on the inventory. A model parameter that regards the corrosion of fuel spacers with high molybdenum contents has been applied, which leads to a higher inventory of Mo-93. In the same calculation model, the contribution from the Studsvik site has furthermore been divided into SNAB and Svafo, which means that the activity in operational waste from Svafo is no longer determined by correlation. In addition, the activity of Mo-93 in the prognosis of operational waste is determined by the same model as for deposited waste, regardless of origin, instead of correlation. The reference inventory of Mo-93 in each waste type, used to calculate the maximum inventory, is given in Bränd (2015).

2.2   Uncertainties for operational waste

The activity in the operational waste is estimated by measurements and calculations as well as correlation to key radionuclides. The key radionuclides Co-60 and Cs-137 can be measured directly on each waste package using gamma detectors. The uncertainty in the gamma measurements can vary depending on whether the waste is homogeneous or heterogeneous (Bäcklin 1990).

Certain actinides as well as Sr-90 are measured using alfa or scintillation detectors on water samples from different process systems at the nuclear power plants and Clab. The uncertainties are also in this case dependent on whether the waste type is homogeneous or not (Ingemansson 2000a). For the nuclear power plants and Clab, the measured sum of Pu-239/240 is used as a key nuclide for correlation of other uranic or transuranic isotopes.

Since a few years, the nuclear power plants (except from BKAB) have started measuring Ni-63, which is analyzed using scintillation detectors. The Ni-59 amount is thereafter determined by correlation to Ni-63. Even if this procedure results in smaller uncertainties, the number of years where correlation of nickel to Co-60 has been used outweighs the few years nickel measurements have been performed. Therefore, the uncertainty in correlation is used in this report for the nickel isotopes.

For the nuclear power plants, the radionuclides C-14, Cl-36 (only in waste containing ion exchange resin), Mo-93, Tc-99, I-129 and Cs-135 are calculated from certain calculation models based on reactor water measurements and other parameters such as the nuclear power plant energy production. The model for Cl-36 is considered to be conservative and no additional uncertainty is needed. For Clab, an adjusted calculation is performed to determine the amount of C-14, Mo-93, Tc-99, I-129 and Cs-135, whereas Cl-36 is determined by correlation to Co-60. For SNAB and Svafo, there is also an adjusted calculation available for Mo-93, Tc-99, I-129 and Cs-135, whereas all the remaining radionuclides are determined by correlation to the measured key nuclides Co-60 and Cs-137.

Radionuclides that are neither measured directly on the produced waste packages, nor correlated to key radionuclides are being reported as a total produced activity each year. Thereafter, the activity is distributed over waste packages that are disposed of in SFR according to different distribution models. There is an uncertainty coupled to the distribution procedure, which according to Ingemansson (2000b) is ±10% (1σ) for actinides and Sr-90. The distribution uncertainty has been applied for all non-waste package specific data in this report.

For the radionuclides Cl-36, Tc-99, I-129 and Cs-135, different methods are applied depending on whether the waste has already been disposed of, or if it is part of the prognosis. For these radionuclides, the uncertainty therefore varies.

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1427105 - Radionuclide inventory for application   Public 4.0 Approved   6 (23)
of extension of the SFR repository - Treatment of
uncertainties

Table 2-1 summarizes the radionuclide specific uncertainties that are considered in the following calculations.

Table 2-1 Uncertainties (1σ) in inventory of operational waste. Values from (SKB 2013)

Nuclide/method	Uncertainty [%]	Uncertainty
Co-60 and Cs-137 in homogeneous waste	20	Uncertainty in gamma measurement on waste package
Co-60 and Cs-137 in heterogeneous waste	+100/-50	Uncertainty in gamma measurement on waste package
Actinides and Sr-90 in ion exchange resin	14	Uncertainty in nuclide specific model of yearly production based on measurements of water samples
Actinides and Sr-90 in trash and scrap metal	20	Uncertainty in nuclide specific model of yearly production based on measurements of water samples
C-14	20	Uncertainty in model of yearly production based on measurements on ion exchange resin samples
Cl-36 in ion exchange resin	-[1]	Uncertainty in model of yearly production based on activation calculation
Mo-93, Tc-99, I-129 and Cs-135	20	Uncertainty in model of yearly production based on activation calculation and measurements of other isotopes
Distribution models	10	Uncertainty in distribution of activity following mass of ion exchange resin or Co-60/Cs-137 activity

[1] The model used to calculate the activity of Cl-36 is estimated to be conservative, and thus no additional uncertainty is needed here.

2.2.1   Correlation factors

Correlation factors are generally used when there is no other method for estimating the radionuclide, but are in some cases also used when the waste has been deemed having a low contribution to the total activity (for instance waste from Studsvik and Clab), see Figure 2-1. The method uses the measured activity of either Co-60, Cs-137 or Pu-239/240 on each waste package and then correlates that measurement to the wanted radionuclide using factors produced in Lindgren et al. (2007) with exception for Tc-99 (Lundgren 2010) and Pu-241 (Thierfeldt et al. 1995).

The factors are produced using measurements of the wanted radionuclide correlated with measurements of Co-60, Cs-137 or Pu-239/240. Measurements from both Swedish and other nuclear power plants are used and thus, the correlation factors come with large uncertainties. The available data has large uncertainties as they are based on measurements of different types of materials (fuel, core, coolant water, resin etc.) and on waste from different reactor types (BWR and PWR). There are also other differences in reactor operations and chemistry of coolant which adds to the general uncertainty of the correlation factors (Lindgren et al. 2007).

In Forsyth (1997) and Cronstrand (2005 and 2007) analyses were performed on the background data of the correlation factors in order to be able to quantify the uncertainties into statistical distributions.

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Swedish Nuclear Fuel and Waste Management Co

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved

7 (23)

The two Cronstrand reports use similar methods: For each radionuclide the available data is evaluated using standard statistical methods and if possible a logarithmic mean and standard deviation is calculated. After that a qualitative assessment is performed to evaluate if the data is representative for SKB use and the amount of data is sufficient. The result of this qualitative assessment is a semi quantitative uncertainty factor of at least 95% confidence. The 2007 report improves on some of the radionuclides uncertainty factors given in the 2005 report by using new data taken strictly from the Swedish nuclear power plants. In Table 2-2 the correlation factor uncertainties used in this report are presented.

Table 2-2 Correlation factor (at 1.645σ) uncertainties from SKB, 2013.

Radionuclide	Correlates with[1]	Uncertainty factor at 1.645σ
H-3	Co-60	50.00
Be-10	Co-60	50.00
Cl-36	Co-60	6.00
Fe-55	Co-60	5.00
Ni-59	Co-60	3.00
Ni-63	Co-60	3.00
Se-79	Cs-137	50.00
Sr-90	Cs-137	5.00
Zr-93	Co-60	50.00
Nb-93m	Co-60	20.00
Nb-94	Co-60	5.00
Tc-99	Co-60	5.00
Pd-107	Cs-137	40.00
Ag-108m	Co-60	50.00
Cd-113m	Cs-137	50.00
Sn-126	Cs-137	40.00
Sb-125	Co-60	10.00
I-129	Cs-137	5.00
Ba-133	Co-60	2.00
Cs-134	Cs-137	1.20
Cs-135	Cs-137	3.00
Pm-147	Cs-137	2.00
Sm-151	Cs-137	2.00
Eu-152	Cs-137	2.00
Eu-154	Cs-137	2.00
Eu-155	Cs-137	2.00
Ho-166m	Co-60	2.00
U-232	Pu-239/240	2.00
U-234	Pu-239/240	2.00
U-235	Pu-239/240	2.00
U-236	Pu-239/240	2.00
U-238	Pu-239/240	2.00
Np-237	Pu-239/240	2.00
Pu-238	Pu-239/240	2.00
Pu-241	Pu-239/240	2.00
Pu-242	Pu-239/240	2.00
Am-241	Pu-239/240	10.00
Am-242m	Pu-239/240	2.00
Am-243	Pu-239/240	2.00
Cm-243	Pu-239/240	2.00
Cm-244	Pu-239/240	2.00
Cm-245	Pu-239/240	2.00
Cm-246	Pu-239/240	2.00

[1] *Waste from SNAB and Svafo correlates actinides against Cs-137.*

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2.2.2 Propagation of uncertainty from measurements to uncertainty factors

The measurement uncertainty of the nuclides Co-60, Cs-137 and Pu-239/240 are viewed as normally distributed when summed with other normally distributed uncertainties. The combined uncertainty factor is then calculated as

$$k_z \frac{\Delta z}{z} = \sqrt{\left(k_x \frac{\Delta x}{x}\right)^2 \Big/ \max(1,N) + \left(k_y \frac{\Delta y}{y}\right)^2}$$

Eq 1

Where k_i = 1.645 for a 95 % confidence level and N is the number of deposited packages of this particular waste type. The absolute error is then calculated using the reported mean value for the radionuclide times the total uncertainty calculated above. The sum of the mean value and the absolute error is used for the maximum inventory.

In case the measurement uncertainty is to be combined with a correlation uncertainty, the normal distribution of the measurement uncertainty is mapped on a log-normal distribution with the same $x_{50\%}$ (median) and $x_{95\%}$. A detailed description of this process is found in Appendix A. The combined uncertainty is

$$z + \Delta z|_k = z \cdot e^{\sqrt{\left[\ln\left(1 + \frac{k_x \frac{\Delta x}{x}\big|_{1\sigma}}{\sqrt{N}}\right)\right]^2 + \left[\ln\left(1 + k_y \frac{\Delta y}{y}\big|_{1\sigma}\right)\right]^2}}$$

Eq 2

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1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved

9 (23)

2.3 Uncertainties for decommissioning waste

The radionuclide inventory for decommissioning waste has been determined using calculation models. Depending on where the material in the waste packages comes from, the nuclide specific activity is calculated and given an uncertainty. These amounts are reported together with maximum and minimum uncertainty factors for each radionuclide (SKB 2013, Appendix D). The maximum uncertainty factors are adjusted to a confidence level of 95% and are used to calculate the maximum radionuclide inventory from decommissioning waste. The maximum uncertainty factors are waste vault specific and are presented in Table 2-3. The radionuclide inventory in the decommissioning waste from SNAB and Svafo has not been estimated to date, which is why these amounts are assumed to be included in their prognosis for operational waste.

Table 2-3 Max uncertainty factors (2σ) for decommissioning waste (SKB 2013 Appendix D). Empty cells indicate no activity from that nuclide in the decommissioning waste in that particular waste vault.

Radionuclide	Max factor silo (2σ)	Max factor BRT (2σ)	Max factor 1-2BMA (2σ)	Max factor 1-5BLA (2σ)
H-3			7.19	3.17
Be-10			4.71	3.00
C-14	9.73	2.00	3.99	6.31
Cl-36	9.39	2.00	4.27	2.72
Ca-41			4.52	2.91
Fe-55	5.01	2.00	2.53	6.99
Co-60	5.16	2.00	2.20	7.81
Ni-59	4.18	2.00	2.32	7.37
Ni-63	4.20	2.00	2.31	7.42
Se-79	9.63		9.25	9.69
Sr-90	4.42	2.00	2.52	9.05
Zr-93	4.87	2.00	2.45	7.04
Nb-93m	4.65	2.00	2.10	7.65
Nb-94	4.59	2.00	2.17	7.38
Mo-93	4.68	2.00	2.17	6.23
Tc-99	8.07	2.00	3.21	9.17
Pd-107	9.79		2.00	8.16
Ag-108m	4.73	2.00	2.39	4.60
Cd-113m	9.78		3.30	9.06
In-115			3.00	
Sn-126	9.50	2.00	2.48	8.19
Sb-125	5.02	2.00	2.42	7.00
I-129	9.68		10.00	9.05
Cs-134	9.88		9.29	8.00
Cs-135	9.69		11.00	8.20
Cs-137	9.71		10.68	8.44
Ba-133	9.82		4.51	3.00
Pm-147	5.61	2.00	2.03	8.42
Sm-151	4.42	2.00	4.63	3.04
Eu-152	4.76	2.00	4.14	3.00
Eu-154	4.71	2.00	3.41	3.41
Eu-155	5.03	2.00	3.12	3.34
Ho-166m	4.85	2.00	5.27	3.00
U-232	5.19	2.00	2.01	8.47
U-235	4.33	2.00	2.35	7.68
U-236	4.98	2.00	1.98	8.36
Np-237	4.38	2.00	1.98	7.94
Pu-238	4.38	2.00	1.98	7.93
Pu-239	4.31	2.00	2.20	7.80
Pu-240	4.31	2.00	2.10	7.99
Pu-241	4.36	2.00	1.92	8.10
Pu-242	4.33	2.00	1.97	7.99
Am-241	4.37	2.00	2.03	7.96
Am-242m	4.21	2.00	1.96	7.84
Am-243	4.38	2.00	1.98	8.01
Cm-243	4.35	2.00	1.97	7.96
Cm-244	4.46	2.00	1.98	8.08
Cm-245	4.47	2.00	2.04	7.87
Cm-246	4.49	2.00	2.03	8.03

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3 Results

3.1 Silo Vault

The proposed Silo inventory is presented in Table 3-1. A comparison with the reference inventory is also given in the same table.

Table 3-1 Silo Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	8.97E+09	4.56E+11	50.88
Be-10	9.89E+05	4.98E+07	50.33
C-14 org	7.55E+11	1.04E+12	1.38
C-14 oorg	2.72E+12	3.75E+12	1.37
Cl-36	8.94E+08	3.91E+09	4.38
Fe-55	2.73E+12	1.52E+13	5.55
Co-60	1.29E+13	2.40E+13	1.86
Ni-59	6.86E+12	2.09E+13	3.05
Ni-63	5.47E+14	1.67E+15	3.05
Se-79	1.05E+09	5.31E+10	50.45
Sr-90	3.61E+12	5.16E+12	1.43
Zr-93	4.48E+09	1.00E+11	22.38
Nb-93m	9.31E+12	3.99E+13	4.28
Nb-94	8.65E+10	3.60E+11	4.17
Mo-93	1.96E+10	4.22E+10	2.16
Tc-99	5.00E+10	1.98E+11	3.95
Pd-107	2.75E+08	1.07E+10	39.00
Ag-108m	2.30E+11	5.08E+12	22.12
Cd-113m	9.58E+09	5.03E+11	52.50
Sn-126	2.05E+08	5.90E+09	28.79
Sb-125	1.32E+11	1.54E+12	11.65
I-129	9.84E+08	3.28E+09	3.34
Cs-134	2.20E+11	5.85E+11	2.66
Cs-135	4.47E+09	9.93E+09	2.22
Cs-137	5.97E+13	9.00E+13	1.51
Ba-133	6.16E+08	1.36E+09	2.21
Pm-147	3.58E+11	1.18E+12	3.28
Sm-151	4.63E+11	1.03E+12	2.23
Eu-152	8.64E+08	2.29E+09	2.65
Eu-154	5.24E+11	1.48E+12	2.82
Eu-155	9.96E+10	3.17E+11	3.18
Ho-166m	6.82E+09	1.41E+10	2.06
U-232	6.20E+05	1.57E+06	2.53
U-234	3.58E+07	8.44E+07	2.36
U-235	1.42E+07	2.98E+07	2.10
U-236	1.58E+07	4.13E+07	2.61
U-238	3.28E+07	7.24E+07	2.21
Np-237	5.36E+08	1.61E+09	3.00
Pu-238	7.29E+10	1.78E+11	2.44
Pu-239	1.70E+10	3.53E+10	2.08
Pu-240	2.39E+10	4.98E+10	2.09
Pu-241	3.07E+11	7.87E+11	2.57
Pu-242	1.23E+08	3.12E+08	2.54
Am-241	2.32E+13	2.81E+14	12.13
Am-242m	3.22E+08	8.37E+08	2.60
Am-243	1.59E+09	3.20E+09	2.01
Cm-243	1.89E+08	4.19E+08	2.22
Cm-244	9.26E+09	2.64E+10	2.85
Cm-245	1.49E+07	4.14E+07	2.78
Cm-246	4.29E+06	1.23E+07	2.87
Total	**6.71E+14**	**2.17E+15**	**3.23**

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved

11 (23)

3.2 BRT Vault

The proposed BRT inventory is presented in Table 3-2. A comparison with the reference inventory is also given in the same table.

Table 3-2 BRT Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
C-14 ind	1.02E+10	1.85E+10	1.82
Cl-36	7.20E+06	1.31E+07	1.82
Fe-55	1.49E+10	2.72E+10	1.82
Co-60	1.93E+11	3.51E+11	1.82
Ni-59	1.60E+11	2.91E+11	1.82
Ni-63	1.44E+13	2.62E+13	1.82
Sr-90	2.32E+10	4.23E+10	1.82
Zr-93	1.84E+08	3.36E+08	1.82
Nb-93m	1.06E+12	1.92E+12	1.82
Nb-94	7.94E+09	1.45E+10	1.82
Mo-93	2.99E+09	5.46E+09	1.82
Tc-99	4.50E+08	8.19E+08	1.82
Ag-108m	1.62E+09	2.96E+09	1.82
Sn-126	7.52E+05	1.37E+06	1.82
Sb-125	1.34E+07	2.45E+07	1.82
Pm-147	1.37E+06	2.49E+06	1.82
Sm-151	3.42E+08	6.23E+08	1.82
Eu-152	5.41E+05	9.86E+05	1.82
Eu-154	9.26E+07	1.69E+08	1.82
Eu-155	2.40E+06	4.37E+06	1.82
Ho-166m	8.00E+03	1.46E+04	1.82
U-232	6.86E+03	1.25E+04	1.82
U-235	1.49E+01	2.71E+01	1.82
U-236	3.92E+05	7.14E+05	1.82
Np-237	4.70E+05	8.57E+05	1.82
Pu-238	2.71E+09	4.95E+09	1.82
Pu-239	4.16E+08	7.57E+08	1.82
Pu-240	5.93E+08	1.08E+09	1.82
Pu-241	9.06E+09	1.65E+10	1.82
Pu-242	3.11E+06	5.67E+06	1.82
Am-241	1.99E+09	3.62E+09	1.82
Am-242m	1.32E+07	2.40E+07	1.82
Am-243	4.14E+07	7.54E+07	1.82
Cm-243	6.38E+06	1.16E+07	1.82
Cm-244	6.74E+08	1.23E+09	1.82
Cm-245	6.82E+05	1.24E+06	1.82
Cm-246	2.24E+05	4.08E+05	1.82
Total	**1.59E+13**	**2.89E+13**	**1.82**

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved   12 (23)

3.3   1BMA Vault

The proposed 1BMA inventory is presented in Table 3-3. A comparison with the reference inventory
is also given in the same table.

Table 3-3 1BMA Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	8.09E+08	4.06E+10	50.18
Be-10	2.21E+05	1.11E+07	50.06
C-14 org	1.47E+11	2.01E+11	1.37
C-14 oorg	1.89E+12	2.59E+12	1.37
Cl-36	3.34E+08	6.67E+08	2.00
Fe-55	5.35E+10	2.72E+11	5.08
Co-60	4.08E+11	4.74E+11	1.16
Ni-59	2.10E+12	6.30E+12	3.00
Ni-63	1.47E+14	4.40E+14	3.00
Se-79	2.10E+08	1.05E+10	50.02
Sr-90	5.49E+11	7.27E+11	1.32
Zr-93	3.68E+08	1.84E+10	50.06
Nb-93m	1.73E+10	3.47E+11	20.08
Nb-94	3.67E+09	1.84E+10	5.01
Mo-93	1.46E+09	2.00E+09	1.37
Tc-99	6.22E+09	1.22E+10	1.96
Pd-107	5.24E+07	2.10E+09	40.02
Ag-108m	1.95E+10	9.75E+11	50.06
Cd-113m	7.98E+08	3.99E+10	50.07
Sn-126	2.62E+07	1.05E+09	40.02
Sb-125	4.37E+07	4.61E+08	10.55
I-129	1.46E+08	3.05E+08	2.08
Cs-134	1.45E+08	1.93E+08	1.33
Cs-135	8.42E+08	1.28E+09	1.53
Cs-137	8.15E+12	8.35E+12	1.02
Ba-133	4.89E+07	9.99E+07	2.04
Pm-147	3.71E+08	7.63E+08	2.06
Sm-151	8.27E+10	1.66E+11	2.00
Eu-152	9.47E+07	2.07E+08	2.19
Eu-154	2.33E+10	4.71E+10	2.02
Eu-155	1.02E+09	2.07E+09	2.03
Ho-166m	1.41E+09	2.83E+09	2.01
U-232	8.85E+04	1.99E+05	2.24
U-234	6.66E+06	1.47E+07	2.20
U-235	3.00E+06	6.28E+06	2.09
U-236	2.65E+06	5.75E+06	2.17
U-238	5.95E+06	1.27E+07	2.14
Np-237	2.72E+07	5.72E+07	2.10
Pu-238	7.51E+09	1.30E+10	1.73
Pu-239	2.78E+09	4.10E+09	1.48
Pu-240	3.87E+09	5.69E+09	1.47
Pu-241	2.40E+10	5.95E+10	2.48
Pu-242	2.00E+07	4.40E+07	2.20
Am-241	2.91E+10	7.48E+10	2.57
Am-242m	4.46E+07	9.90E+07	2.22
Am-243	2.02E+08	2.97E+08	1.47
Cm-243	1.85E+07	3.16E+07	1.71
Cm-244	6.73E+08	1.48E+09	2.20
Cm-245	1.99E+06	4.37E+06	2.20
Cm-246	5.27E+05	1.16E+06	2.20
Total	**1.60E+14**	**4.61E+14**	**2.88**

3.4   2BMA Vault

The proposed 2BMA inventory is presented in Table 3-4. A comparison with the reference inventory is also given in the same table.

Table 3-4 2BMA Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	3.31E+12	2.02E+13	6.09
Be-10	2.19E+04	9.85E+05	44.89
C-14 org	3.96E+09	7.49E+09	1.89
C-14 oorg	1.44E+10	2.63E+10	1.83
C-14 ind	5.09E+09	1.76E+10	3.46
Cl-36	2.02E+08	8.00E+08	3.96
Ca-41	1.56E+10	6.07E+10	3.90
Fe-55	1.05E+11	4.64E+11	4.44
Co-60	1.99E+12	3.74E+12	1.88
Ni-59	9.50E+11	2.12E+12	2.23
Ni-63	9.21E+13	2.02E+14	2.19
Se-79	7.29E+06	3.77E+08	51.78
Sr-90	3.60E+11	8.69E+11	2.41
Zr-93	1.06E+09	3.87E+09	3.66
Nb-93m	1.31E+13	2.50E+13	1.91
Nb-94	9.13E+10	1.80E+11	1.97
Mo-93	4.52E+09	8.65E+09	1.91
Tc-99	1.42E+09	5.00E+09	3.53
Pd-107	2.55E+09	4.72E+09	1.85
Ag-108m	4.07E+10	1.73E+11	4.25
Cd-113m	9.32E+07	4.15E+09	44.56
In-115	3.13E+05	8.29E+05	2.65
Sn-126	1.75E+07	7.46E+07	4.26
Sb-125	2.62E+08	1.27E+09	4.87
I-129	7.68E+06	4.50E+07	5.86
Cs-134	2.25E+08	3.30E+08	1.46
Cs-135	5.33E+07	3.22E+08	6.04
Cs-137	8.96E+11	4.58E+12	5.11
Ba-133	1.43E+08	5.30E+08	3.71
Pm-147	4.07E+08	8.60E+08	2.11
Sm-151	3.55E+10	1.36E+11	3.84
Eu-152	1.33E+11	4.78E+11	3.58
Eu-154	6.83E+09	1.93E+10	2.83
Eu-155	3.74E+08	9.72E+08	2.60
Ho-166m	5.22E+08	2.11E+09	4.04
U-232	1.46E+05	3.46E+05	2.36
U-234	3.04E+06	9.73E+06	3.20
U-235	7.82E+04	2.32E+05	2.96
U-236	6.00E+06	1.21E+07	2.02
U-238	1.23E+06	3.92E+06	3.19
Np-237	7.67E+06	1.58E+07	2.06
Pu-238	4.42E+10	9.12E+10	2.06
Pu-239	6.77E+09	1.49E+10	2.20
Pu-240	9.20E+09	1.97E+10	2.14
Pu-241	1.66E+11	3.52E+11	2.12
Pu-242	5.02E+07	1.03E+08	2.05
Am-241	4.13E+10	1.99E+11	4.81
Am-242m	1.83E+08	3.62E+08	1.98
Am-243	6.62E+08	1.31E+09	1.99
Cm-243	1.03E+08	2.12E+08	2.06
Cm-244	1.07E+10	2.15E+10	2.01
Cm-245	1.01E+07	2.00E+07	1.98
Cm-246	3.34E+06	6.50E+06	1.94
Total	**1.13E+14**	**2.61E+14**	**2.30**

3.5 1BTF Vault

The proposed 1BTF inventory is presented in Table 3-5. A comparison with the reference inventory is also given in the same table.

Table 3-5 1BTF Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	6.81E+07	3.41E+09	50.05
Be-10	1.37E+04	6.88E+05	50.09
C-14 org	9.84E+09	1.35E+10	1.37
C-14 oorg	1.89E+11	2.59E+11	1.37
Cl-36	1.44E+07	4.81E+07	3.34
Fe-55	8.34E+07	4.17E+08	5.00
Co-60	1.67E+10	1.71E+10	1.02
Ni-59	3.30E+10	1.03E+11	3.13
Ni-63	2.04E+12	6.43E+12	3.16
Se-79	1.57E+07	7.87E+08	50.15
Sr-90	3.48E+10	5.14E+10	1.48
Zr-93	2.29E+07	1.15E+09	50.09
Nb-93m	1.43E+09	2.87E+10	20.03
Nb-94	2.53E+08	1.27E+09	5.02
Mo-93	2.56E+08	3.50E+08	1.37
Tc-99	2.31E+09	8.48E+09	3.68
Pd-107	3.92E+06	1.57E+08	40.13
Ag-108m	1.51E+09	7.56E+10	50.08
Cd-113m	7.69E+07	3.86E+09	50.21
Sn-126	1.96E+06	7.87E+07	40.13
Sb-125	7.47E+06	7.47E+07	10.00
I-129	2.27E+07	9.17E+07	4.04
Cs-134	7.09E+04	8.54E+04	1.20
Cs-135	1.03E+08	2.46E+08	2.39
Cs-137	7.13E+11	8.07E+11	1.13
Ba-133	4.04E+06	8.11E+06	2.01
Pm-147	3.84E+06	7.68E+06	2.00
Sm-151	6.52E+09	1.33E+10	2.04
Eu-152	6.20E+07	1.24E+08	2.01
Eu-154	1.98E+09	4.03E+09	2.04
Eu-155	4.97E+07	1.00E+08	2.02
Ho-166m	8.79E+07	1.77E+08	2.02
U-232	1.62E+04	3.28E+04	2.02
U-234	9.86E+05	2.00E+06	2.03
U-235	1.84E+07	3.69E+07	2.00
U-236	4.02E+05	8.22E+05	2.04
U-238	8.55E+05	1.76E+06	2.06
Np-237	1.06E+06	2.19E+06	2.06
Pu-238	2.09E+09	3.98E+09	1.90
Pu-239	4.68E+08	8.52E+08	1.82
Pu-240	5.20E+08	9.20E+08	1.77
Pu-241	7.30E+09	1.48E+10	2.02
Pu-242	2.96E+06	6.00E+06	2.03
Am-241	6.14E+09	5.16E+10	8.40
Am-242m	7.34E+06	1.49E+07	2.03
Am-243	3.25E+07	5.67E+07	1.74
Cm-243	3.82E+06	7.57E+06	1.98
Cm-244	2.68E+08	5.21E+08	1.95
Cm-245	2.94E+05	5.97E+05	2.03
Cm-246	7.82E+04	1.59E+05	2.03
Total	**3.06E+12**	**7.90E+12**	**2.58**

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved

15 (23)

3.6   2BTF Vault

The proposed 2BTF inventory is presented in Table 3-6. A comparison with the reference inventory is also given in the same table.

Table 3-6 2BTF Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	1.07E+08	5.37E+09	50.06
Be-10	2.48E+04	1.24E+06	50.11
C-14 org	6.07E+09	8.31E+09	1.37
C-14 oorg	2.69E+11	3.68E+11	1.37
Cl-36	1.66E+07	4.06E+07	2.45
Fe-55	1.14E+08	5.72E+08	5.00
Co-60	2.36E+10	2.41E+10	1.02
Ni-59	3.83E+10	1.16E+11	3.03
Ni-63	2.27E+12	6.88E+12	3.04
Se-79	1.54E+07	7.72E+08	50.00
Sr-90	5.76E+10	1.29E+11	2.23
Zr-93	4.14E+07	2.07E+09	50.11
Nb-93m	2.34E+09	4.70E+10	20.04
Nb-94	4.13E+08	2.07E+09	5.03
Mo-93	2.36E+08	3.22E+08	1.37
Tc-99	5.45E+08	7.53E+08	1.38
Pd-107	3.86E+06	1.54E+08	40.00
Ag-108m	2.21E+09	1.11E+11	50.11
Cd-113m	6.36E+07	3.18E+09	50.00
Sn-126	1.93E+06	7.71E+07	40.00
Sb-125	1.04E+07	1.04E+08	10.00
I-129	1.02E+07	1.40E+07	1.37
Cs-134	8.85E+04	1.06E+05	1.20
Cs-135	1.85E+07	2.54E+07	1.37
Cs-137	6.23E+11	6.33E+11	1.01
Ba-133	6.20E+06	1.25E+07	2.01
Pm-147	4.57E+06	9.14E+06	2.00
Sm-151	6.15E+09	1.23E+10	2.00
Eu-152	6.54E+06	1.31E+07	2.00
Eu-154	1.80E+09	3.60E+09	2.00
Eu-155	5.83E+07	1.17E+08	2.00
Ho-166m	1.59E+08	3.21E+08	2.02
U-232	6.74E+03	1.42E+04	2.10
U-234	4.55E+05	9.57E+05	2.10
U-235	1.11E+05	2.33E+05	2.09
U-236	3.55E+05	7.44E+05	2.09
U-238	8.75E+05	1.83E+06	2.09
Np-237	1.98E+06	4.18E+06	2.11
Pu-238	4.55E+08	6.41E+08	1.41
Pu-239	1.89E+08	2.77E+08	1.46
Pu-240	2.64E+08	3.87E+08	1.46
Pu-241	2.42E+09	5.08E+09	2.10
Pu-242	1.37E+06	2.87E+06	2.10
Am-241	1.83E+09	6.09E+09	3.33
Am-242m	3.21E+06	6.75E+06	2.10
Am-243	1.78E+07	2.53E+07	1.42
Cm-243	4.15E+05	7.99E+05	1.92
Cm-244	2.84E+07	3.75E+07	1.32
Cm-245	1.36E+05	2.85E+05	2.10
Cm-246	3.60E+04	7.57E+04	2.10
Total	**3.30E+12**	**8.36E+12**	**2.53**

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved   16 (23)

3.7   1BLA Vault

The proposed1BLA inventory is presented in Table 3-7. A comparison with the reference inventory is also given in the same table.

Table 3-7 1BLA Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	2.00E+08	1.01E+10	50.41
Be-10	6.52E+02	3.42E+04	52.37
C-14 org	7.92E+07	1.08E+08	1.37
C-14 oorg	4.02E+09	5.50E+09	1.37
Cl-36	2.17E+07	2.88E+07	1.33
Fe-55	8.78E+06	5.05E+07	5.75
Co-60	1.02E+09	2.00E+09	1.96
Ni-59	4.00E+09	1.27E+10	3.17
Ni-63	3.05E+11	9.59E+11	3.15
Se-79	4.00E+05	2.06E+07	51.55
Sr-90	7.42E+08	2.92E+09	3.94
Zr-93	1.09E+06	5.69E+07	52.37
Nb-93m	7.68E+07	1.66E+09	21.62
Nb-94	3.14E+07	1.95E+08	6.22
Mo-93	1.01E+08	1.39E+08	1.37
Tc-99	1.85E+09	6.66E+09	3.59
Pd-107	1.00E+05	4.14E+06	41.32
Ag-108m	1.94E+08	9.86E+09	50.92
Cd-113m	1.96E+06	1.04E+08	53.16
Sn-126	5.00E+04	2.07E+06	41.32
Sb-125	4.74E+05	5.55E+06	11.71
I-129	4.35E+05	1.38E+06	3.18
Cs-134	1.58E+04	4.06E+04	2.57
Cs-135	3.07E+06	6.37E+06	2.08
Cs-137	1.84E+10	3.15E+10	1.71
Ba-133	2.20E+05	5.90E+05	2.68
Pm-147	3.02E+05	9.07E+05	3.01
Sm-151	1.68E+08	3.97E+08	2.37
Eu-152	1.01E+08	2.21E+08	2.18
Eu-154	4.00E+07	1.03E+08	2.57
Eu-155	1.54E+06	4.45E+06	2.88
Ho-166m	4.18E+06	1.04E+07	2.49
U-232	2.34E+03	7.61E+03	3.25
U-234	1.33E+05	4.29E+05	3.23
U-235	2.98E+08	7.21E+08	2.42
U-236	3.99E+04	1.29E+05	3.23
U-238	7.33E+08	1.55E+09	2.11
Np-237	6.75E+04	2.09E+05	3.09
Pu-238	3.47E+08	1.12E+09	3.24
Pu-239	6.60E+07	2.12E+08	3.22
Pu-240	6.74E+07	2.15E+08	3.20
Pu-241	1.29E+09	4.22E+09	3.28
Pu-242	3.99E+05	1.29E+06	3.23
Am-241	5.23E+08	6.08E+09	11.62
Am-242m	1.02E+06	3.32E+06	3.24
Am-243	4.00E+06	1.28E+07	3.19
Cm-243	7.58E+05	2.46E+06	3.25
Cm-244	5.39E+07	1.75E+08	3.25
Cm-245	3.97E+04	1.28E+05	3.23
Cm-246	1.05E+04	3.41E+04	3.23
Total	**3.39E+11**	**1.06E+12**	**3.12**

1427105 - Radionuclide inventory for application
of extension of the SFR repository - Treatment of
uncertainties

Public 4.0 Approved

17 (23)

3.8   2-5BLA Vaults

The proposed inventory for 2-5BLA vaults is presented in Table 3-8. A comparison with the reference inventory is also given in the same table.

Table 3-8 2-5BLA Inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	1.94E+11	5.43E+11	2.79
Be-10	1.26E+03	2.49E+04	19.75
C-14 org	2.25E+08	1.21E+09	5.37
C-14 oorg	9.27E+08	4.98E+09	5.37
C-14 ind	1.19E+09	6.41E+09	5.37
Cl-36	4.60E+07	1.13E+08	2.46
Ca-41	3.91E+09	1.01E+10	2.57
Fe-55	4.45E+08	2.64E+09	5.93
Co-60	2.59E+10	1.66E+11	6.41
Ni-59	1.15E+10	6.62E+10	5.74
Ni-63	1.12E+12	6.57E+12	5.86
Se-79	5.94E+06	5.85E+07	9.85
Sr-90	2.40E+10	1.80E+11	7.51
Zr-93	2.95E+07	2.09E+08	7.11
Nb-93m	1.34E+11	8.69E+11	6.48
Nb-94	9.82E+08	6.15E+09	6.27
Mo-93	9.01E+07	3.09E+08	3.43
Tc-99	4.98E+08	3.06E+09	6.15
Pd-107	1.72E+06	1.39E+07	8.06
Ag-108m	1.53E+09	8.46E+09	5.54
Cd-113m	6.13E+06	1.79E+08	29.18
Sn-126	7.93E+06	5.58E+07	7.04
Sb-125	4.46E+06	3.03E+07	6.78
I-129	1.93E+06	1.45E+07	7.49
Cs-134	1.40E+06	9.25E+06	6.63
Cs-135	1.76E+08	1.21E+09	6.91
Cs-137	4.95E+11	3.45E+12	6.97
Ba-133	1.26E+07	3.33E+07	2.65
Pm-147	1.19E+06	5.51E+06	4.62
Sm-151	5.89E+09	1.58E+10	2.69
Eu-152	1.73E+10	4.57E+10	2.65
Eu-154	2.67E+08	8.01E+08	3.00
Eu-155	1.16E+07	3.48E+07	2.99
Ho-166m	9.03E+07	2.39E+08	2.65
U-232	9.35E+03	3.66E+04	3.92
U-234	4.38E+05	1.44E+06	3.29
U-235	3.23E+08	1.03E+09	3.17
U-236	2.06E+05	9.61E+05	4.65
U-238	1.77E+08	4.47E+08	2.52
Np-237	2.61E+05	1.06E+06	4.09
Pu-238	1.52E+09	6.22E+09	4.09
Pu-239	2.77E+08	1.10E+09	3.98
Pu-240	2.95E+08	1.23E+09	4.16
Pu-241	5.74E+09	2.36E+10	4.12
Pu-242	1.71E+06	7.01E+06	4.10
Am-241	1.94E+09	2.21E+10	11.38
Am-242m	4.84E+06	2.07E+07	4.28
Am-243	1.86E+07	8.02E+07	4.31
Cm-243	3.40E+06	1.40E+07	4.13
Cm-244	2.80E+08	1.26E+09	4.52
Cm-245	2.18E+05	1.01E+06	4.63
Cm-246	6.60E+04	3.27E+05	4.95
Total	**2.05E+12**	**1.20E+13**	**5.86**

3.9   All vaults

The proposed inventory for the whole repository is given in Table 3-9. This includes the following waste vaults: Silo, BRT, 1BMA, 2BMA, 1BTF, 2BTF, 1BLA and 2-5BLA.

Table 3-9 Repository inventory

Radionuclide	Reference inventory [Bq]	Maximum inventory [Bq]	Uncertainty factor (1.645σ)
H-3	3.52E+12	2.12E+13	6.04
Be-10	1.27E+06	6.38E+07	50.15
C-14 org	9.22E+11	1.27E+12	1.38
C-14 oorg	5.09E+12	7.00E+12	1.37
C-14 ind	1.65E+10	4.26E+10	2.59
Cl-36	1.54E+09	5.62E+09	3.66
Ca-41	1.95E+10	7.08E+10	3.63
Fe-55	2.91E+12	1.59E+13	5.48
Co-60	1.55E+13	2.87E+13	1.85
Ni-59	1.02E+13	2.99E+13	2.95
Ni-63	8.06E+14	2.36E+15	2.93
Se-79	1.31E+09	6.56E+10	50.19
Sr-90	4.66E+12	7.16E+12	1.54
Zr-93	6.19E+09	1.26E+11	20.43
Nb-93m	2.36E+13	6.81E+13	2.88
Nb-94	1.91E+11	5.83E+11	3.05
Mo-93	2.92E+10	5.95E+10	2.03
Tc-99	6.33E+10	2.34E+11	3.71
Pd-107	2.89E+09	1.79E+10	6.19
Ag-108m	2.97E+11	6.44E+12	21.67
Cd-113m	1.06E+10	5.55E+11	52.20
In-115	3.13E+05	8.29E+05	2.65
Sn-126	2.61E+08	7.24E+09	27.71
Sb-125	1.32E+11	1.54E+12	11.64
I-129	1.17E+09	3.76E+09	3.20
Cs-134	2.20E+11	5.86E+11	2.66
Cs-135	5.67E+09	1.30E+10	2.30
Cs-137	7.06E+13	1.08E+14	1.53
Ba-133	8.31E+08	2.05E+09	2.47
Pm-147	3.59E+11	1.18E+12	3.28
Sm-151	6.00E+11	1.38E+12	2.29
Eu-152	1.52E+11	5.26E+11	3.47
Eu-154	5.58E+11	1.55E+12	2.78
Eu-155	1.01E+11	3.20E+11	3.17
Ho-166m	9.09E+09	1.98E+10	2.17
U-232	8.96E+05	2.22E+06	2.48
U-234	4.75E+07	1.14E+08	2.39
U-235	6.57E+08	1.82E+09	2.77
U-236	2.59E+07	6.25E+07	2.42
U-238	9.52E+08	2.09E+09	2.19
Np-237	5.75E+08	1.69E+09	2.94
Pu-238	1.32E+11	2.99E+11	2.27
Pu-239	2.80E+10	5.75E+10	2.06
Pu-240	3.87E+10	7.91E+10	2.04
Pu-241	5.23E+11	1.26E+12	2.42
Pu-242	2.03E+08	4.82E+08	2.38
Am-241	2.33E+13	2.82E+14	12.10
Am-242m	5.79E+08	1.37E+09	2.36
Am-243	2.57E+09	5.06E+09	1.97
Cm-243	3.25E+08	6.99E+08	2.15
Cm-244	2.19E+10	5.26E+10	2.40
Cm-245	2.84E+07	6.91E+07	2.44
Cm-246	8.58E+06	2.10E+07	2.45
Total	**9.70E+14**	**2.95E+15**	**3.04**

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Appendix A

A.1 Normally distributed random variables

A normally distributed random variable has the probability density function

$$P(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

Eq 3

where μ is the mean (and median) and σ^2 the variance of the distribution. The cumulative distribution function is

$$D(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)\right],$$

Eq 4

where erf is the error function. A value that with a probability of 95% is higher than or equal to a sample from the distribution is here called $x_{95\%}$, and is given by

$$x_{95\%} = \mu + \text{erf}^{-1}(0.9)\sqrt{2}\sigma \approx \mu + 1.645\sigma.$$

Eq 5

The relative error at 95% confidence level is then

$$\frac{\Delta x}{x} = \frac{1.645\sigma}{\mu}.$$

Eq 6

A.2 Log-normally distributed variables

A log-normal distribution has the probability density function

$$P(x) = \frac{1}{\sqrt{2\pi}Sx} e^{-\frac{(\ln x - M)^2}{2S^2}},$$

Eq 7

where e^M is the median, $e^{M+S^2/2}$ is the mean and $e^{2M+S^2}\left(e^{S^2} - 1\right)$ is the variance of the distribution. The cumulative distribution function is given by

$$D(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\ln x - M}{\sqrt{2}S}\right)\right]. \qquad\qquad \text{Eq 8}$$

A value that with a probability of 95% is higher than or equal to a sample from the distribution is then given by

$$x_{95\%} = e^{M+\text{erf}^{-1}(0.9)\sqrt{2}S} \approx e^M e^{1.645S}. \qquad\qquad \text{Eq 9}$$

The relative error at 95% confidence level is then

$$\frac{\Delta x}{x} = e^{1.645S} - 1. \qquad\qquad \text{Eq 10}$$

A.3   The sum of two continuous stochastic variables

A random variable Z from a continuous distribution that is the sum of two independent continuous stochastic variables X and Y, with probability density functions $P_X(x)$ and $P_Y(y)$, has a probability density function given by

$$P_Z(z) = (P_X * P_Y)(z) = \int_{-\infty}^{\infty} P_X(t)P_Y(z - t)dt. \qquad\qquad \text{Eq 11}$$

A.3.1   Sum of two normally distributed variables

The sum of two normally distributed variables is also normally distributed with mean $\mu_Z = \mu_X + \mu_Y$ and variance $\sigma_Z^2 = \sigma_X^2 + \sigma_Y^2$. The relative error at 95% confidence is

$$\left.\frac{\Delta z}{z}\right|_{95\%} = 1.645 \frac{\sqrt{\sigma_X^2 + \sigma_Y^2}}{\mu_X + \mu_Y}. \qquad\qquad \text{Eq 12}$$

A.4   The product of two continuous stochastic variables

A continuous stochastic variable Z that is the product of two continuous stochastic variables X and Y, has a probability density function given by

$$P_Z(z) = \int_{-\infty}^{\infty} P_X(t)\, P_Y(z/t)\frac{1}{|t|}dt. \qquad\qquad \text{Eq 13}$$

A.4.1   The product of two log-normally distributed variables

The product of two log-normally distributed variables is also log-normally distributed with

$$\begin{aligned} M_Z &= M_X + M_Y \\ S_Z^2 &= S_X^2 + S_Y^2 \end{aligned} \qquad\qquad \text{Eq 14}$$

The relative error at 95% confidence is

$$\left.\frac{\Delta z}{z}\right|_{95\%} = e^{1.645\sqrt{S_X^2 + S_Y^2}} - 1. \qquad \text{Eq 15}$$

The product of one normally distributed and one log-normally distributed variable is a distribution with a probability distribution given by

$$P_Z(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{t}{S_X\sigma_Y z}e^{-\left[\frac{(\ln z/t - M_X)^2}{2S_X^2} + \frac{(t-\mu_Y)^2}{2\sigma_Y^2}\right]}\frac{1}{|t|}dt \qquad \text{Eq 16}$$

This equation has no analytic solution.

A.5   Mapping a normal distribution onto a log-normal distribution

In order to find an analytic expression to estimate $z_{95\%}$ for a stochastic variable that is the product of a normally distributed and a log-normally distributed variable, we may map the normal distribution onto a log-normal distribution so that we then may use Eq 13 to find $z_{95\%}$. To get the same $x_{50\%}$ and $x_{95\%}$ the log-normal distribution must fulfill

$$\begin{aligned} M_X &= \ln\mu_X \\ S_X &= \frac{\ln x_{95\%} - \ln\mu_X}{x_{95\%} - \mu_X}\sigma_X, \end{aligned} \qquad \text{Eq 17}$$
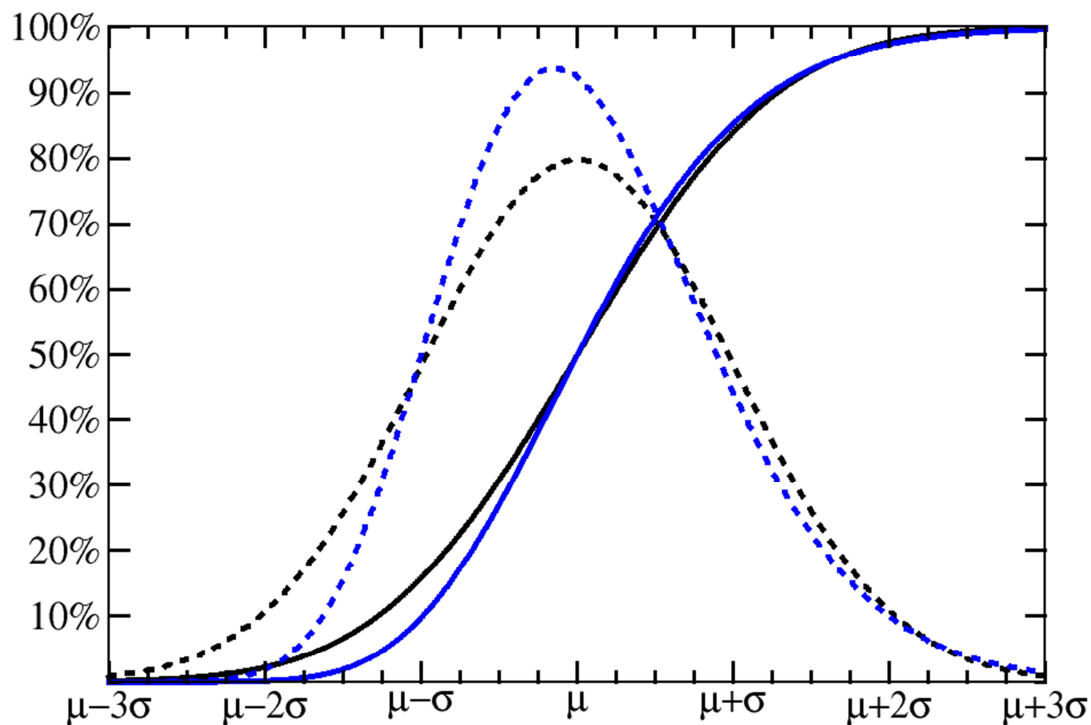
so that the relative error at 95% confidence is

$$\left.\frac{\Delta z}{z}\right|_{95\%} = e^{\sqrt{\left[\ln\left(1+1.645\frac{\sigma_X}{\mu_X}\right)\right]^2 + \left[\ln\left(1+\frac{\Delta y}{y}\Big|_{95\%}\right)\right]^2}} - 1, \qquad \text{Eq 18}$$

or

$$z + \Delta z|_{95\%} = z \cdot e^{\sqrt{\left[\ln\left(1+\frac{\Delta x}{x}\Big|_{95\%}\right)\right]^2 + \left[\ln\left(1+\frac{\Delta y}{y}\Big|_{95\%}\right)\right]^2}}. \qquad \text{Eq 19}$$

By matching the distributions at other confidence levels (at $k\sigma$) it can be shown that

$$z + \Delta z|_k = z \cdot e^{\sqrt{\left[\ln\left(1+k\frac{\Delta x}{x}\Big|_{1\sigma}\right)\right]^2 + \left[\ln\left(1+k\frac{\Delta y}{y}\Big|_{1\sigma}\right)\right]^2}}. \qquad \text{Eq 20}$$

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Figur A-1 Mapping of a normal distribution onto a log-normal distribution, matching $x_{50\%}$ and $x_{95\%}$.