Radiological Characterization of Buildings at the Ranstad Uranium Works

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1 Introduction

The Ranstad mill was built in 1962 – 1965 with the purpose to process the uranium bearing alum shale of the nearby Ranstad mine. A total of 200 tons of uranium was produced 1965 – 1969. Due to low uranium prices on the world market, the operation stopped in 1969. There were unrealized plans to restart the production in the 1970s. The restoration of the uranium mine is completed while the mill has been in a mixture of service operation and decommissioning during the last decades except for parts of the facility where Ranstad Mineral AB has recovered uranium from process wastes from nuclear fuel factories.

A first version of the plan for dismantling and demolition was issued in 2009 and a radiological survey project was started.

The initial evaluation of the radiological survey was presented at ***Seminar on Decommissioning of nuclear facilitie***s held at Studsvik, 14 – 16 September 2010 [1]. In a poster on ***Radiological measurements and clearance of materials and buildings at an uranium extraction plant*** the problems associated with clearance of materials with low level uranium contamination was discussed.

This report is a follow-up of the presentations at the Studsvik seminar in September 2010. Focus is on methods for evaluation of the measurements, on how the measurements are intended to be used for clearance and also on statistical methods to be applied in the decision making. Finally the application of the principles will be described in two examples related to the sorting works of the Ranstad mill.

2 Inventory of Radionuclides

2.1 General

Calculation of the inventory of radionuclides at the Ranstad works is done in six steps:

- Activity measurements with scintillation detectors
- Gamma spectrometric measurements with HPGe detectors
- Dividing the Ranstad works into radiologically homogenous areas called “system identities”
- Defining nuclide vectors
- Measuring the efficiency of the scintillation detectors
- Evaluation of areas and weights of all system identities

These steps are combined to calculate the nuclide inventory of each system identity. The total inventory at the Ranstad works is given by summing all the system identities.

2.2 Activity Measurements with Scintillation Detectors

The radiological mapping was described in [1]. Here focus is on measurements with scintillation detectors in the three buildings where the alum shale was processed and the uranium extracted: The sorting works, the leaching hall and the uranium extraction plant. In the systematic measurements, the mean surface activity of a square with 0.25 m sides was measured with 8x4 measurements with a scintillation detector. A total of 1065, 1214 and 604 squares were measured for the sorting works, the leaching hall and the uranium extraction plant respectively.

2.3 Gamma Spectrometric Measurements

Laboratory and in situ gamma spectroscopy have been used to investigate nuclide specific activities. The results were used to define nuclide vectors of various materials and locations.

2.4 System Identities

In order to calculate the inventory of radioactivity, the buildings were divided into “system identities”. Within a system identity the material is relatively homogenous. The contamination is of the same magnitude and there is one general nuclide vector. If decontamination is needed, one common method is used for all material. All waste from the decontamination of one system identity can be disposed of in the same way.

2.5 Nuclide Vectors

Gamma spectroscopy does not identify all radioactive nuclides of a sample or a building surface. Therefore full nuclide vectors have to be decided based on a combination of measurements and theoretical considerations.

At Ranstad the processed alum shale and the building materials essentially only contain natural radioactivity. The naturally occurring radionuclides in question are:

- Natural uranium (U-235, U-238) with associated decay chains
- Natural thorium (Th-232) with associated decay chain
- Natural potassium with the radioactive isotope K-40

In the alum shale the uranium is in equilibrium with its decay chain.

The separation of uranium from alum shale that took place in the leaching process has resulted in different nuclide vectors in the leaching hall and in the uranium extraction plant. In the leaching hall the nuclide vectors are depleted of uranium. In the uranium extraction plant the nuclide vectors have an enrichment of uranium.

While deciding the nuclide vectors of the leaching hall and the uranium extraction plant, the decay time elapsed from the operation of Ranstad 1965 – 1969 to date, about 45 years, must be considered.

Simulations of the decay chains, including calculation of the decay energies, have been made with the computer program FISPACT.

Several nuclide vectors are used to describe the nuclide specific activities of all materials at the Ranstad works.

The nuclide vector of alum shale is based on the following information:

- K = 4 wt %.
- U = 300 ppm.
- Th = 8 ppm.
- Gamma spectroscopy has shown that an average of 51 % of the radon daughters from U-238 series have been vented away. For Th-232 series, the corresponding figure is 32 %.

Based on the above, activity and radiation data for alum shale is as shown in **Table 1**.

Table 1: Naturally occurring radioactivity in alum shale processed at the Ranstad works

U_nat	Bq/kg	Th_nat	Bq/kg	K_nat	Bq/kg
Tl207	1.70E+02	Tl208	2.96E+00	K40	1.24E+03
Pb210	1.81E+03	Pb212	8.23E+00		
Pb211	1.71E+02	Bi212	8.23E+00		
Pb214	1.81E+03	Po212	5.27E+00		
Bi210	1.81E+03	Po216	8.23E+00		
Bi211	1.71E+02	Rn220	8.23E+00		
Bi214	1.81E+03	Ra224	1.21E+01		
Po210	1.81E+03	Ra228	1.21E+01		
Po214	1.81E+03	Ac228	1.21E+01		
Po215	1.71E+02	Th228	1.21E+01		
Po218	1.81E+03	Th232	1.21E+01		
Rn219	1.71E+02				
Rn222	1.81E+03				
Ra223	1.71E+02				
Ra226	3.70E+03				
Ac227	1.71E+02				
Th227	1.68E+02				
Th230	3.70E+03				
Th231	1.71E+02				
Th234	3.70E+03				
Pa231	1.71E+02				
Pa234m	3.70E+03				
U 234	3.70E+03				
U 235	1.71E+02				
U 238	3.70E+03				
Total	**5.37E+04**	**Total**	**1.21E+02**	**Total**	**1.24E+03**
Total - α	**3.08E+04**	**Total - α**	**7.27E+01**	**Total - α**	**0.00E+00**
	MeV/s,kg		**MeV/s,kg**		**MeV/s,kg**
Alpha	1.40E+05	Alpha	3.74E+02	Alpha	0.00E+00
Beta	8.74E+03	Beta	1.68E+01	Beta	6.45E+02
Gamma	7.03E+03	Gamma	2.97E+01	Gamma	1.94E+02

2.6 Efficiency of the Scintillation Detectors

The efficiency of the scintillation detectors is determined by comparing the scintillation detector value and the gamma spectroscopy results before and after an abrasion of the measured surface. The gamma spectroscopy result is weighted with the actual nuclide vector to get the efficiency of the scintillation detector in total activity per m^2 per counts per second.

2.7 Area and Weight Data

Area and weight data is used to quantify the activity at the Ranstad works. Area and weight data are given by layouts, onsite measurements and known densities.

2.8 Inventory of Nuclides at the Ranstad Works

Based on the scintillation detector measurements, the calibration of the scintillation detectors and the nuclide vectors developed, activity inventories of the different system identities are calculated. The total number of system identities is about 65.

Calculated inventories for three system identities are shown in **Table 2**. The three identities have different characteristics:

- SV.1.1 –Sorting works ground floor. Activity in the form of contamination from alum shale and naturally occurring activity in concrete. The alum shale contains about 300 ppm uranium.
- LV.8.1 – Filtering gravel at bottom of leaching pools N1 and N2. Activity dominated by uranium daughter nuclides. Laboratory tests show that the material holds about 90 ppm uranium.
- RMA.1.2 – Ground floor of the uranium extraction plant. Activity in the form of contamination from uranium concentrate with about 45 years of decay time and naturally occurring activity in concrete.

Table 2: Ranstad - Calculated Inventories of System Identities SV.1.1, LV.8.1 and RMA.1.2

Identity	**SV.1.1**			**LV.8.1**		**RMA.1.2**		
Total activity (cont.+NORM) [Bq]	1.1E+10			6.5E+09		3.3E+09		
Specific activity [Bq/kg]	2.0E+03			3.1E+04		2.1E+03		
Contamination [Bq]	1.1E+08			6.5E+09		2.6E+08		
Concentration of specific activity [Bq/kg]	2.0E+01			3.1E+04		1.7E+02		
Uranium contamination [g]	8.0E+02			1.8E+04		1.1E+03		
Total uranium content (cont.+NORM) [ppm]	4.2E+00			8.8E+01		4.7E+00		
	Surface activity	Contamination	Total activity	Specific activity	Contamination	Surface activity	Contamination	Total activity
Nuclide	**[Bq/m^2]**	**[Bq]**	**[Bq]**	**[Bq/kg]**	**[Bq]**	**[Bq/m^2]**	**[Bq]**	**[Bq]**
K40	1.09E+03	3.3E+06	4.10E+09	1.09E+03	2.29E+08	0.00E+00	0.00E+00	1.20E+09
Tl208	6.94E+00	2.1E+04	9.22E+07	6.93E+00	1.46E+06	1.05E+03	1.87E+06	2.88E+07
Pb212	1.93E+01	5.9E+04	2.57E+08	1.93E+01	4.06E+06	2.91E+03	5.21E+06	8.02E+07
Bi212	1.93E+01	5.9E+04	2.57E+08	1.93E+01	4.06E+06	2.91E+03	5.21E+06	8.02E+07
Po212	1.24E+01	3.8E+04	1.64E+08	1.23E+01	2.60E+06	1.86E+03	3.33E+06	5.13E+07
Po216	1.93E+01	5.9E+04	2.57E+08	1.93E+01	4.06E+06	2.91E+03	5.21E+06	8.02E+07
Rn220	1.93E+01	5.9E+04	2.57E+08	1.93E+01	4.06E+06	2.91E+03	5.21E+06	8.02E+07
Ra224	2.84E+01	8.6E+04	2.57E+08	2.84E+01	5.98E+06	4.28E+03	7.67E+06	8.26E+07
Ra228	2.84E+01	8.6E+04	2.57E+08	2.84E+01	5.98E+06	4.28E+03	7.67E+06	8.26E+07
Ac228	2.84E+01	8.6E+04	2.57E+08	2.84E+01	5.98E+06	4.28E+03	7.67E+06	8.26E+07
Th228	2.84E+01	8.6E+04	2.57E+08	2.84E+01	5.98E+06	4.28E+03	7.67E+06	8.26E+07
Th232	2.84E+01	8.6E+04	2.57E+08	2.84E+01	5.98E+06	4.28E+03	7.67E+06	8.26E+07
Tl207	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.15E+07	7.24E+02	1.30E+06	4.81E+06
Pb210	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Pb211	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Pb214	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Bi210	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Bi211	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Bi214	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Po210	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Po214	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Po215	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Po218	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Rn219	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Rn222	1.60E+03	4.9E+06	2.66E+08	2.15E+03	4.52E+08	3.10E+03	5.55E+06	8.20E+07
Ra223	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Ra226	3.26E+03	9.9E+06	2.71E+08	3.25E+03	6.85E+08	3.10E+03	5.55E+06	8.20E+07
Ac227	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Th227	1.48E+02	4.5E+05	1.23E+07	1.48E+02	3.11E+07	7.24E+02	1.30E+06	4.77E+06
Th230	3.26E+03	9.9E+06	2.71E+08	3.25E+03	6.85E+08	3.10E+03	5.55E+06	8.20E+07
Th231	1.50E+02	4.6E+05	1.25E+07	5.00E+01	1.05E+07	1.75E+03	3.13E+06	6.65E+06
Th234	3.26E+03	9.9E+06	2.71E+08	1.08E+03	2.28E+08	7.49E+03	1.34E+07	8.98E+07
Pa231	1.50E+02	4.6E+05	1.25E+07	1.50E+02	3.16E+07	7.24E+02	1.30E+06	4.82E+06
Pa234m	3.26E+03	9.9E+06	2.71E+08	1.08E+03	2.28E+08	7.49E+03	1.34E+07	8.98E+07
U234	3.26E+03	9.9E+06	2.71E+08	1.11E+03	2.33E+08	4.47E+04	8.00E+07	1.56E+08
U235	1.50E+02	4.6E+05	1.25E+07	5.00E+01	1.05E+07	1.75E+03	3.13E+06	6.65E+06
U236	0.00E+00	0.0E+00	0.00E+00	0.00E+00	0.00E+00	2.40E+02	4.30E+05	4.30E+05
U238	3.26E+03	9.9E+06	2.71E+08	1.08E+03	2.28E+08	7.49E+03	1.34E+07	8.98E+07
	Source	**Factor**		**Source**	**Factor**	**Source**	**Factor**	
	Alum shale	8.79E-01		Leaching remains	8.78E-01	U ext. plant	7.49E+03	
Volyme [m^3]	2302			191		673		
Area [m^2]	3044			957		1790		
Weight [kg]	5293850			210667		1547515		

A summary of the calculated activity inventories is shown in **Table 3**.

Table 3: Ranstad – Summary of calculated activity inventories

Activity inventory [Bq]

Bq	Sorting works			Leaching hall			Uranium extraction plant			Summary		
	Contamination	Concrete	Total	Contamination	Concrete	Total	Contamination	Concrete	Total	Contamination	Concrete	Total
K40	7.1E+06	1.2E+10	1.2E+10	1.6E+09	1.7E+10	1.9E+10	0.0E+00	4.2E+09	4.2E+09	1.6E+09	3.3E+10	3.5E+10
Tl208	4.5E+04	2.6E+08	2.6E+08	1.0E+07	3.9E+08	4.0E+08	2.9E+07	9.5E+07	1.2E+08	3.9E+07	7.5E+08	7.9E+08
Pb212	1.3E+05	7.3E+08	7.3E+08	2.8E+07	1.1E+09	1.1E+09	8.2E+07	2.7E+08	3.5E+08	1.1E+08	2.1E+09	2.2E+09
Bi212	1.3E+05	7.3E+08	7.3E+08	2.8E+07	1.1E+09	1.1E+09	8.2E+07	2.7E+08	3.5E+08	1.1E+08	2.1E+09	2.2E+09
Po212	8.0E+04	4.7E+08	4.7E+08	1.8E+07	7.0E+08	7.2E+08	5.2E+07	1.7E+08	2.2E+08	7.0E+07	1.3E+09	1.4E+09
Po216	1.3E+05	7.3E+08	7.3E+08	2.8E+07	1.1E+09	1.1E+09	8.2E+07	2.7E+08	3.5E+08	1.1E+08	2.1E+09	2.2E+09
Rn220	1.3E+05	7.3E+08	7.3E+08	2.8E+07	1.1E+09	1.1E+09	8.2E+07	2.7E+08	3.5E+08	1.1E+08	2.1E+09	2.2E+09
Ra224	1.8E+05	7.3E+08	7.3E+08	4.1E+07	1.1E+09	1.1E+09	1.2E+08	2.7E+08	3.9E+08	1.6E+08	2.1E+09	2.2E+09
Ra228	1.8E+05	7.3E+08	7.3E+08	4.1E+07	1.1E+09	1.1E+09	1.2E+08	2.7E+08	3.9E+08	1.6E+08	2.1E+09	2.2E+09
Ac228	1.8E+05	7.3E+08	7.3E+08	4.1E+07	1.1E+09	1.1E+09	1.2E+08	2.7E+08	3.9E+08	1.6E+08	2.1E+09	2.2E+09
Th228	1.8E+05	7.3E+08	7.3E+08	4.1E+07	1.1E+09	1.1E+09	1.2E+08	2.7E+08	3.9E+08	1.6E+08	2.1E+09	2.2E+09
Th232	1.8E+05	7.3E+08	7.3E+08	4.1E+07	1.1E+09	1.1E+09	1.2E+08	2.7E+08	3.9E+08	1.6E+08	2.1E+09	2.2E+09
Tl207	9.7E+05	3.5E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Pb210	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Pb211	9.7E+05	3.6E+07	3.7E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Pb214	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Bi210	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Bi211	9.7E+05	3.5E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Bi214	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Po210	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Po214	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Po215	9.7E+05	3.5E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Po218	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Rn219	9.7E+05	3.6E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Rn222	1.0E+07	7.7E+08	7.8E+08	3.1E+09	1.1E+09	4.2E+09	8.7E+07	2.7E+08	3.6E+08	3.2E+09	2.2E+09	5.3E+09
Ra223	9.7E+05	3.6E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Ra226	2.1E+07	7.7E+08	7.9E+08	4.7E+09	1.1E+09	5.9E+09	8.7E+07	2.7E+08	3.6E+08	4.9E+09	2.2E+09	7.0E+09
Ac227	9.7E+05	3.6E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Th227	9.6E+05	3.5E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.8E+07	3.3E+08
Th230	2.1E+07	7.7E+08	7.9E+08	4.7E+09	1.1E+09	5.9E+09	8.7E+07	2.7E+08	3.6E+08	4.8E+09	2.2E+09	7.0E+09
Th231	9.7E+05	3.5E+07	3.6E+07	8.7E+07	5.1E+07	1.4E+08	4.9E+07	1.2E+07	6.1E+07	1.4E+08	9.9E+07	2.4E+08
Th234	2.1E+07	7.7E+08	7.9E+08	1.9E+09	1.1E+09	3.0E+09	2.1E+08	2.7E+08	4.8E+08	2.1E+09	2.2E+09	4.3E+09
Pa231	9.7E+05	3.5E+07	3.6E+07	2.2E+08	5.1E+07	2.7E+08	2.0E+07	1.2E+07	3.3E+07	2.4E+08	9.9E+07	3.4E+08
Pa234m	2.1E+07	7.7E+08	7.9E+08	1.9E+09	1.1E+09	3.0E+09	2.1E+08	2.7E+08	4.8E+08	2.1E+09	2.2E+09	4.3E+09
U234	2.1E+07	7.7E+08	7.9E+08	1.9E+09	1.1E+09	3.0E+09	1.3E+09	2.7E+08	1.5E+09	3.2E+09	2.2E+09	5.3E+09
U235	9.7E+05	3.5E+07	3.6E+07	8.7E+07	5.1E+07	1.4E+08	4.9E+07	1.2E+07	6.1E+07	1.4E+08	9.9E+07	2.4E+08
U236	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.7E+06	0.0E+00	6.7E+06	6.7E+06	0.0E+00	6.7E+06
U238	2.1E+07	7.7E+08	7.9E+08	1.9E+09	1.1E+09	3.0E+09	2.1E+08	2.7E+08	4.8E+08	2.1E+09	2.2E+09	4.3E+09
Activity [Bq]	2.3E+08	3.0E+10	3.0E+10	4.6E+10	4.4E+10	9.0E+10	4.0E+09	1.1E+10	1.5E+10	5.0E+10	8.5E+10	1.4E+11
Uran [kg]	1.7E+00	6.2E+01	6.4E+01	1.5E+02	9.0E+01	2.4E+02	1.7E+01	2.2E+01	3.9E+01	1.7E+02	1.7E+02	3.5E+02
Weight [kg]			1.6E+07			2.9E+07			5.7E+06			5.0E+07

Total weight of all material is of about 50 000 tons.

The total contamination is about 50 GBq. This can be compared with the total activity of natural occurring nuclides in the concrete which is about 85 GBq.

Contamination is highest in the filtering gravel in the bottom of the leaching pools in the leaching hall (Identity LV.8.1 shown in **Table 2**).

3 Disposal of Contaminated Material

There is a total of approximately 50 000 tons of material to be disposed of in connection with the dismantling and demolishing of the sorting works, the leaching hall and the uranium extraction plant. The material is from the past uranium production contaminated with a little less than 200 kg of uranium.

Alternatives considered for disposal of the contaminated material:

- Clearance for free use without restrictions
- Use of only slightly contaminated building rubble for construction purposes within the Ranstad site
- Depositing of contaminated building rubble on a for the purpose constructed landfill for inert waste at the Ranstad site
- Depositing of contaminated building rubble, metallic objects and other materials at a regular landfill for hazardous waste
- Depositing in a deep geological repository for long lived radioactive waste of minor amounts of contaminated material

For each of the alternatives, calculations of radionuclide migration and dose are used to estimate the radiological consequences of disposal of the radioactive material. In principal such calculations indicate how the dose depends on the total activity disposed of.

Operative clearance rules are needed to control the realization of a disposal plan. Therefore the calculations of radionuclide migration and dose are used to establish clearance rules for each of the disposal alternatives. Conceptually, disposal of the material associated with a system identity at a given alternative is permitted provided that the mean contamination is below the maximum mean level permitted for that alternative while at the same time the maximum value for a single square is below a maximum level.

The basis for defining a maximum mean value is that this limits the total activity disposed of for an alternative. This in turn makes it possible to limit the dose consequences to the public due to general migration or as a result of major intrusions. By defining a maximum level for a single square it is possible to limit the dose consequence of a limited intrusion by a few persons to a level acceptable for those few persons.

4 Statistical Methods Used for Clearance

The *mean surface activity* of a system identity is

$$a = r_N \gamma_D$$

(Bq/m^2), where

$$r_N = r_T - r_B$$

is the *net radiation* (c/s) (r_T and r_B are the *total* and *background radiation*, respectively) and γ_D is the *detector efficiency* ((Bq/m^2)/(c/s)).

For decision making, the level of contamination is evaluated in line with section 3.2 "Clearance of Buildings for Demolition Only" of Radiation protection 113 [2]. Table 2 "Radionuclide specific clearance levels for building demolition expressed as total activity in the structure per unit surface area" and the associated summation formula are used. The level of contamination is expressed as the total sum arrived at by using the summation formula.

As described above there is a nuclide vector defined for each of the system identities. Then there is a constant b_R, that depends on the surface activities and the clearance levels of the radionuclides present, and such that, if

$$a \leq {}^1/_{b_R}$$

then the contamination of the system identity is below the clearance level for building demolition.

Here we will only discuss the uncertainty in a and in the clearance parameter

$$a_R = a b_R$$

Other parameters of interest, e.g. the amount of uranium, are calculated similarly.

It is clearly not possible to measure the background radiation of the identity under study. The best we can do is to sample some spots in the whole building, that are assumed to be clean, and, by calculating the mean, obtain an estimate of $r_B$that is subject to uncertainty.

It is further not practical to measure all areas (floors as well as walls and ceilings) of the identity. Even if this was done, there would be some remaining uncertainty due to the necessarily finite integration time. Again, the best we can do is to obtain an estimate of r_T by sampling. The difference of these estimates is a natural estimate $\hat{r}_N$ of the net radiation r_N. Also this estimate is clearly uncertain.

Note also that the detector efficiency cannot be known with certainty. Again, the best one can do is to make some controlled calibration measurements, from which an estimate $\hat{\gamma}_D$ may be calculated.

Summing up, the best we can do is to calculate an estimate $\hat{a} = \hat{r}_N \hat{\gamma}_D$ of a. It is of course important to characterize the error in this estimate.

Also the clearance constant b_R is not known with certainty, since it depends on the proportions of the nuclides present. So we need also characterize the error in the estimate $\hat{b}_R$ of b_R.

Standard statistical methods may be used to calculate upper confidence limits for $r_N \; and \; \gamma_D$. By multiplication, we get a statistical upper limit for the error in their product a. There are drawbacks with this method. Firstly, it is difficult to calculate the exact confidence in the upper limit. Secondly, the confidence limit is unnecessarily conservative, since it is not likely that both errors are maximal and tend in the same direction.

Furthermore, the error in the clearance constant b_R is hard to measure and need to be assessed by expert judgment.

For these reasons we advocate a Bayesian approach to the calculation of upper limits of the parameters of interest, and to use Monte Carlo as the main computational tool.

In a Monte Carlo computation of uncertainty, point values are replaced by probability distributions and the resulting uncertainty is calculated by simulation. Note that the uncertainties in a and a_R then are given by probability density functions (pdf's), that are estimated numerically. The error in these estimates depends on the number of simulations. Usually 10 or 100 thousands suffice.

Uncertainty in the basic parameters may be assessed in two ways:

- By Bayesian inference techniques
- By expert judgment

In this work we used Bayesian techniques to assess the uncertainty in r_N and γ_D, and expert judgment to assess the uncertainty in b_R.

We want to emphasize here that it is very important that the squares measured are randomly sampled for the Bayesian inference to provide accurate uncertainty estimates. It is believed that practicians avoid random sampling since a purely random mechanism typically does not distribute the squares evenly. This disadvantage can easily be taken care with a combination of systematic and purely random sampling, so called stratified random sampling. An example of systematic sampling as well as purely random and stratified random sampling is given in the Appendix. We furthermore want to point out that systematic sampling usually gives good estimates of means. The disadvantage, however, is that it is not easy to assess the uncertainty.

Now consider Figures 1-5. Figure 1 shows a histogram of 10^5 simulations of the detector efficiency γ_D, Figure 2 shows a histogram of the net radiation r_N (c/s) in a system identity and Figure 3 shows a histogram of their product a. Moreover, Figure 4 shows a histogram of $1/b_R$ and Figure 5 shows a histogram of $a_R = b_R a$.

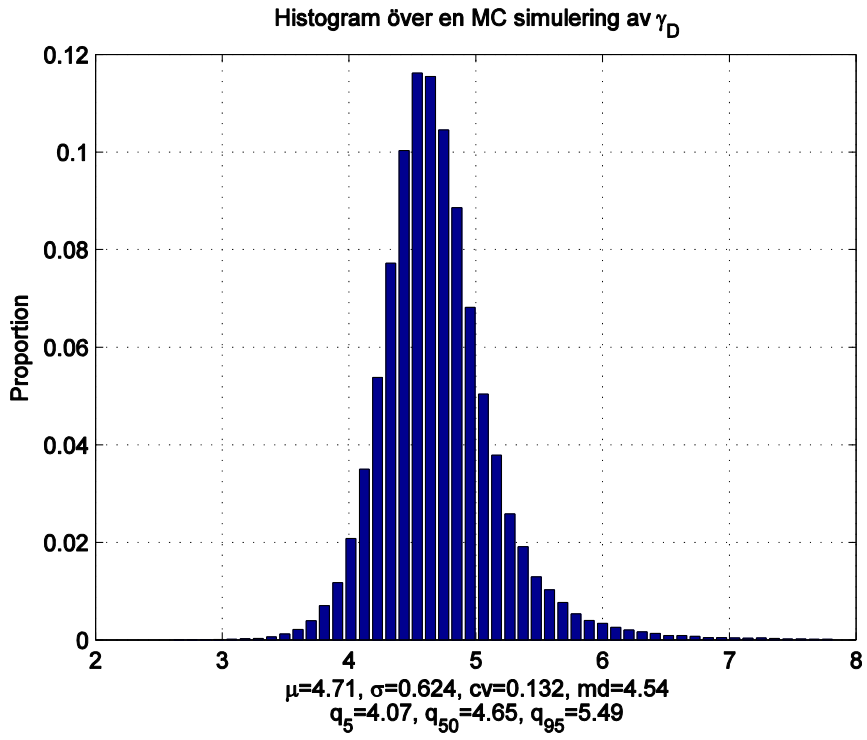

Figure 1: Histogram of 10^5 simulations of the detector efficiency γ_D (kBq/m2)/(c/s)

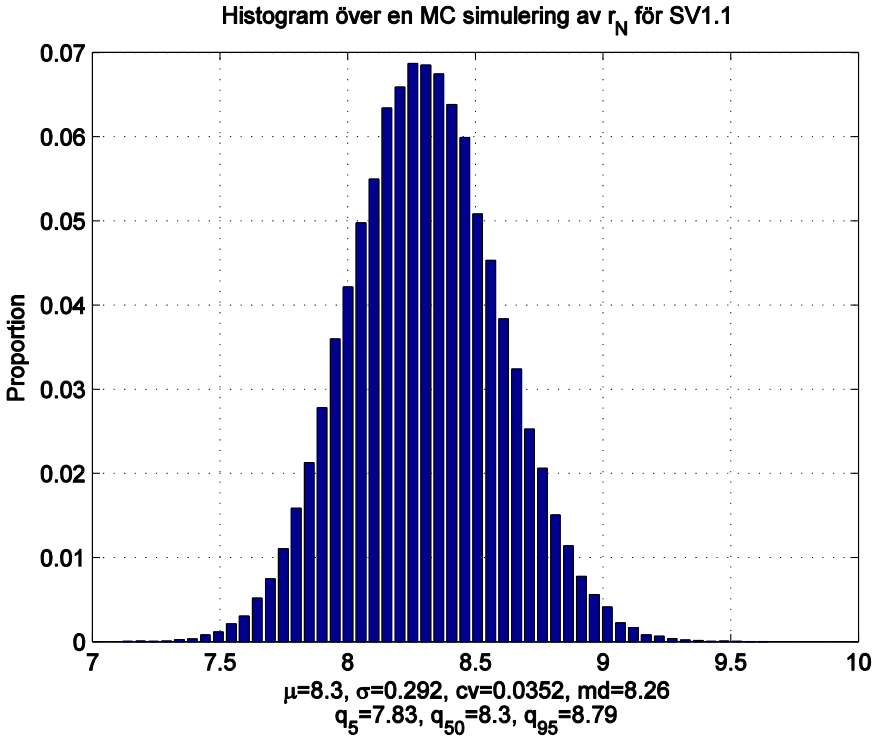

Figure 2: Histogram of 10^5 simulations of net radiation r_N (c/s) for system identity SV1.1

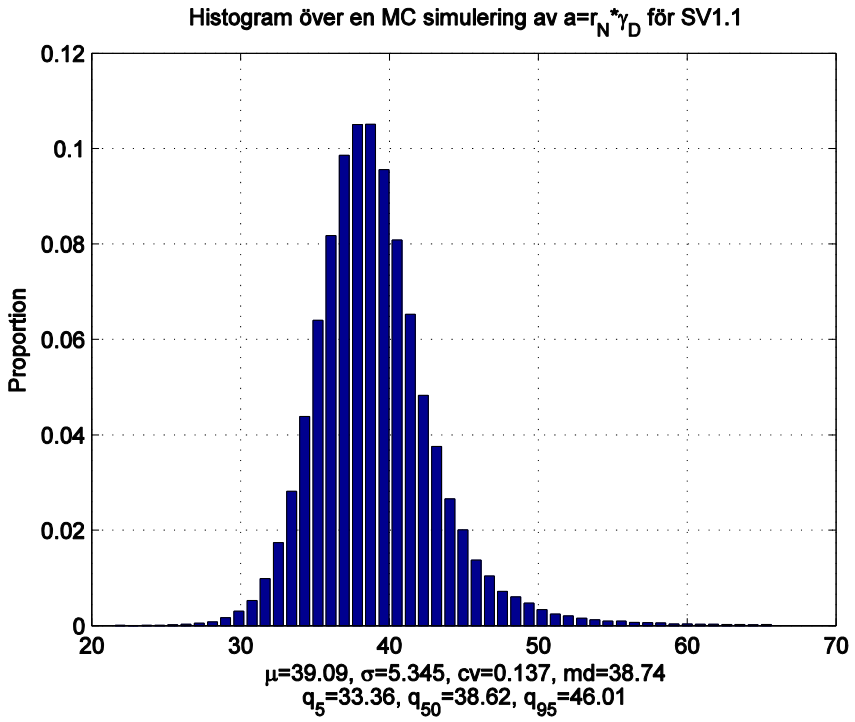

Figure 3: Histogram of 10^5 simulations of the mean activity a (kBq/m2) in system identity SV1.1

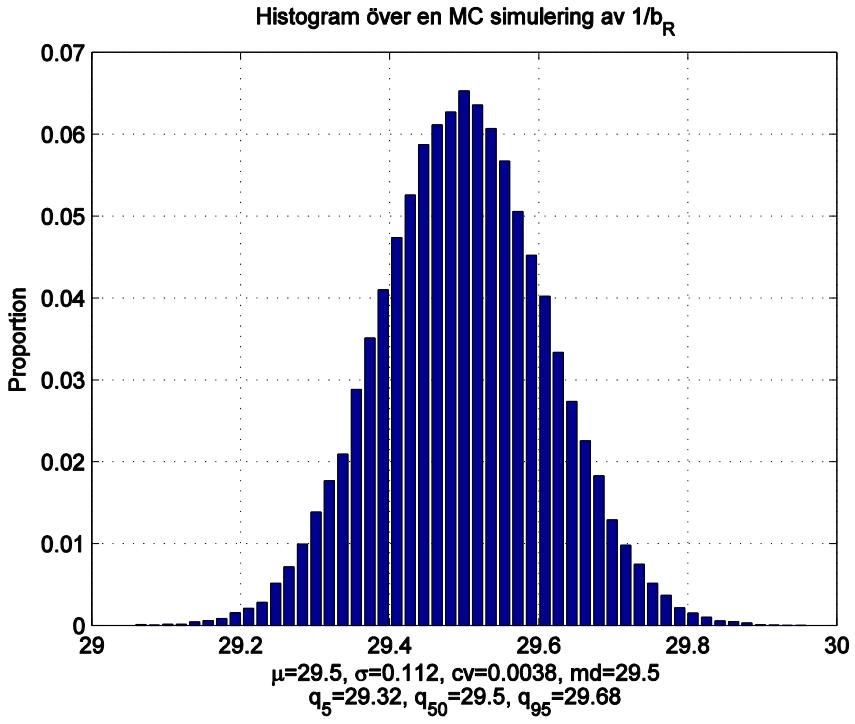

Figure 4: Histogram of 10^5 simulations of $1/b_R$

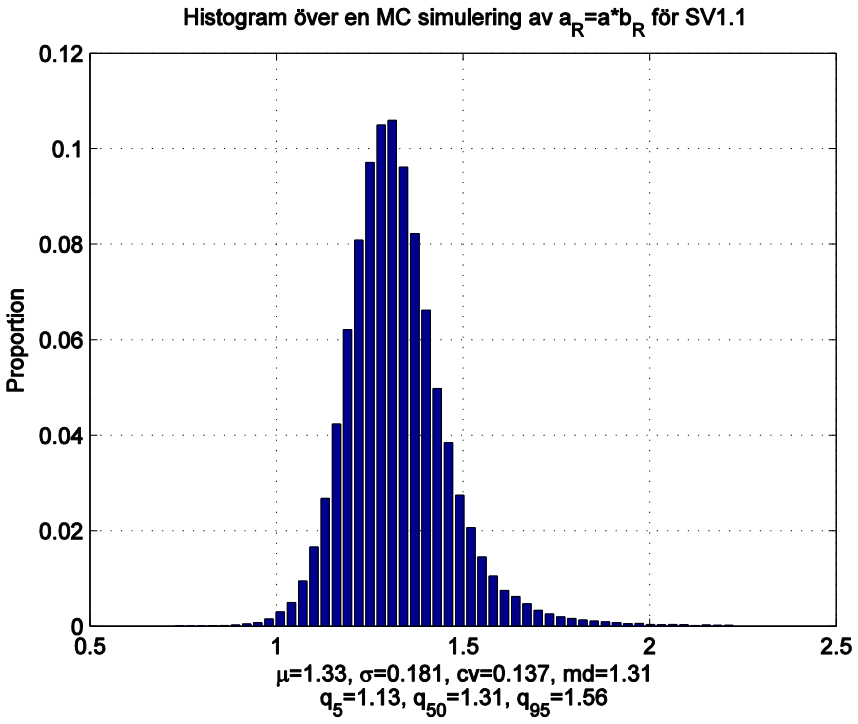

Figure 5: Histogram of 10^5 simulations of the clearance parameter a_R for system identity SV1.1

The median q_{50} of the mean activity a in identity SV1.1 is 38.6 kBq/m^2 and the expected value (or mean value) μ is 39.09 kBq/m^2. The upper 95% credibility limit q_{95} for the mean activity is 46.0 kBq/m^2. These and other results from the Monte Carlo simulation can be read off from Figure 3. The mean value and the 95% upper credibility limit (in the text denoted UCL95) for the mean of the clearance parameter a_R can be read off from Figure 5 (see μ and q_{95} in the figure). We used means as typical values and their UCL95 values as the highest plausible value. There is thus a 5% risk that the true value of a parameter is larger than its highest plausible value.

Note also that the coefficient of variation (cv) for a_R is 0.137. Now, a_R is a product of three factors, the coefficient of variations are 0.035 for r_N, 0.132 for γ_D and 0.010 for b_R. Two conclusions are immediate: (1) the uncertainty in $\gamma_D$dominates; and (2) maybe the number of samples in system identity SV1.1 is unnecessarily many.

Another argument for the Bayesian approach to uncertainty is the possibility to predict the next value x_N of a measurement of r_N. Those kinds of calculations are not possible within the frequentist paradigm. Figure 6 shows a histogram of simulations of x_N and Figure 7 shows a histogram of a possible new activity measurement $a_x = x_N\gamma_D$. We used the 95th percentile in the uncertainty distribution for a_X as the highest plausible value for a potential local activity measurement. We see from the figure that the 95th percentile equals 106.6 kBq/m^2. The latter is of course much bigger than the corresponding percentile of a (which equals 46.0 kBq/m^2). Figure 8 shows a histogram of $a_{Rx} = x_N\gamma_D b_R$. The 95th percentile (in the text denoted P95) equals 3.61. This value is regarded as the highest plausible local value of the clearance parameter a_R.

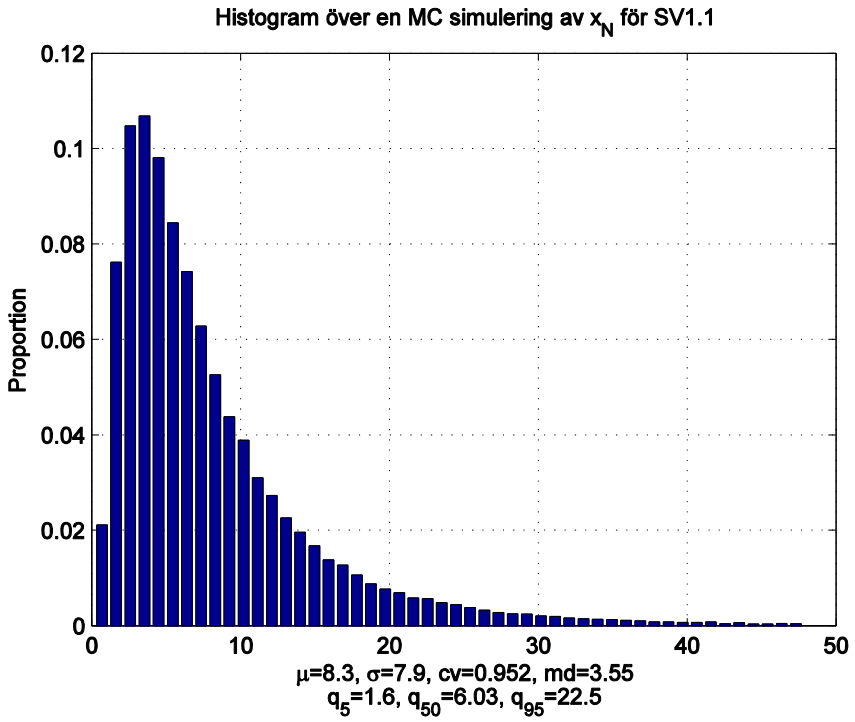

Figure 6: Histogram of 10^5 simulations of a possible new net radiation measurement x_N (c/s)

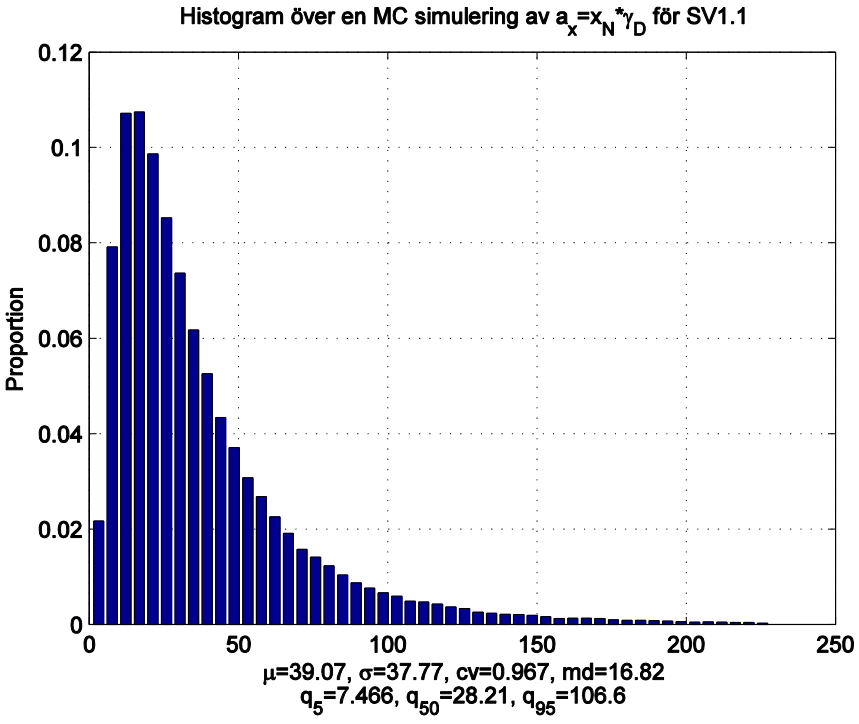

Figure 7: Histogram of 10^5 simulations of $a_x = x_N \gamma_D$ (kBq/m2)

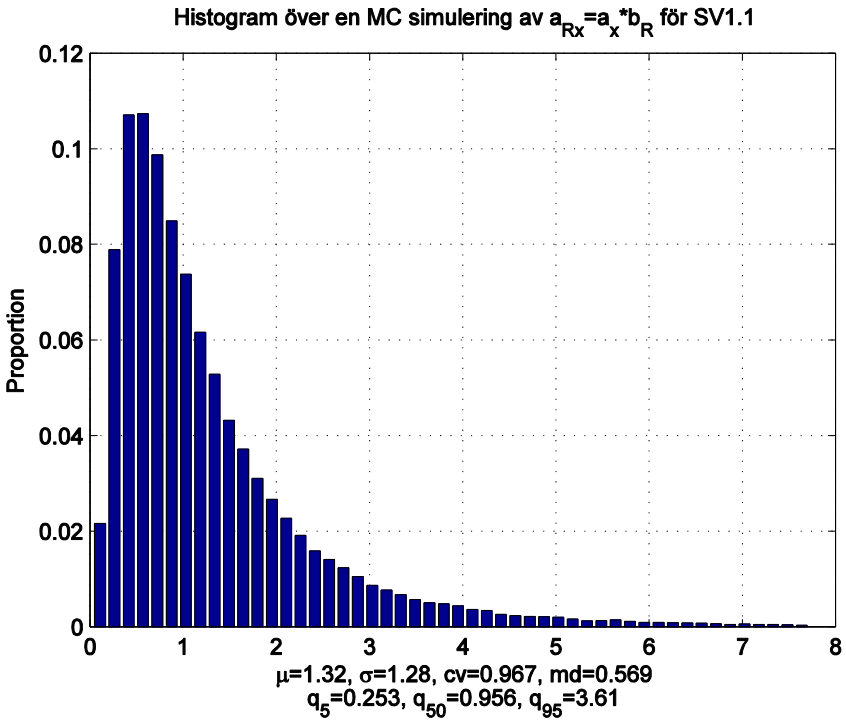

Figure 8: Histogram of 10^5 simulations of $a_{Rx} = x_N \gamma_D b_R$

Note that r_N and x_N have the same expectation μ. The standard deviation σ of the latter is of course much bigger, since it combines the uncertainty in the parameters and the uncertainty in the outcome of a new measurement.

5 Contamination of the Sorting Works

The principles described in the previous chapters are illustrated with the following examples concerning the concrete building structures of the sorting works.

Below find the system identities used for the first example. All the system identities are made from concrete and the surfaces are to varying degrees contaminated with uranium bearing alum shale.

System Identity	Description	Number of measurement squares
SV.1.1	Floors at ground level	307
SV.1.2	Floors above ground level	436
SV.2	Walls and columns	161
SV.4.1	Conveyor belt tunnel	13

In the diagram below the sums calculated with the summation formula (the clearance parameter) are shown. Mean, UCL95 and P95 values are indicated. Tentative clearance levels for use of the building rubble for construction purposes within the Ranstad site are also included.

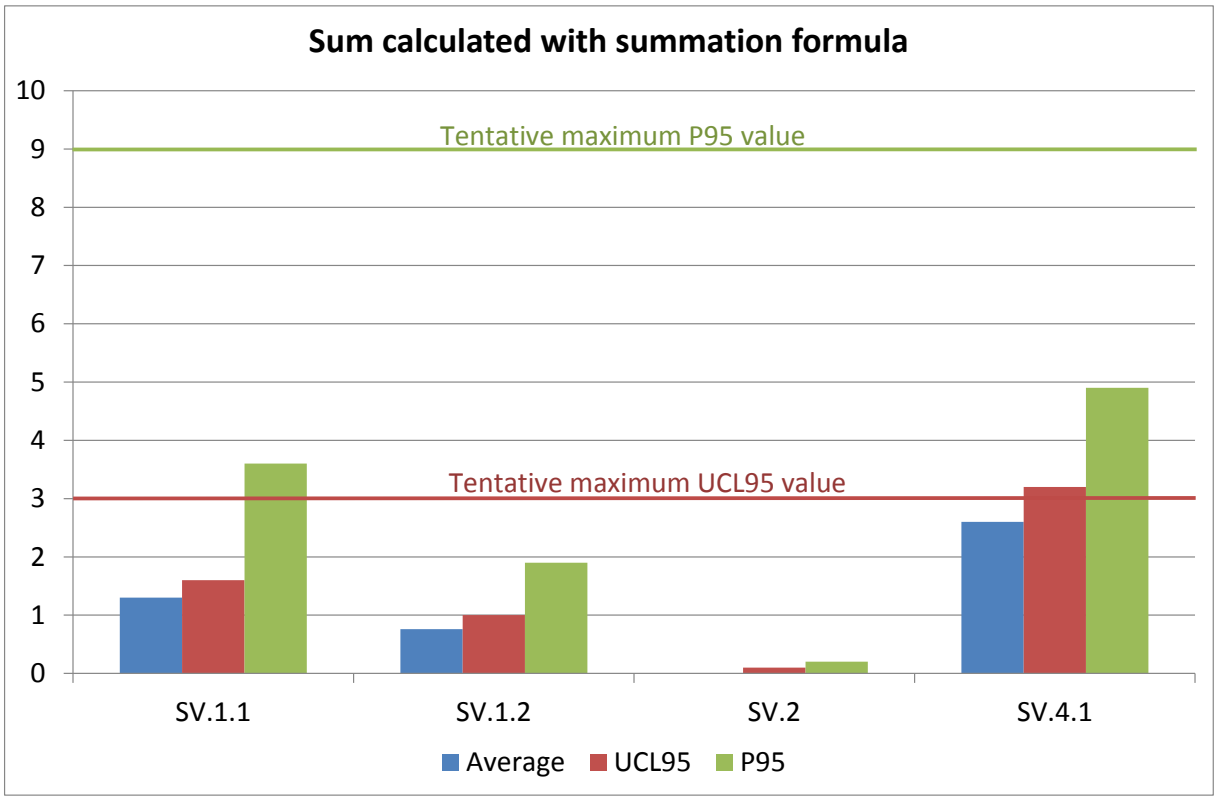

Figure 9: Contamination level of four sorting works system identities

For system identity SV.4.1 the UCL95 value is obviously slightly higher than the tentative clearance level for the disposal alternative considered. Additional decontamination is needed before disposal.

In the next diagram the effect of decontamination is shown. System identity SV.7.2 is the concrete surface below where the sink and float facility was located. The sink and float facility was used for a wet process used to separate the uranium rich alum shale from the lime stone also present in the shale.

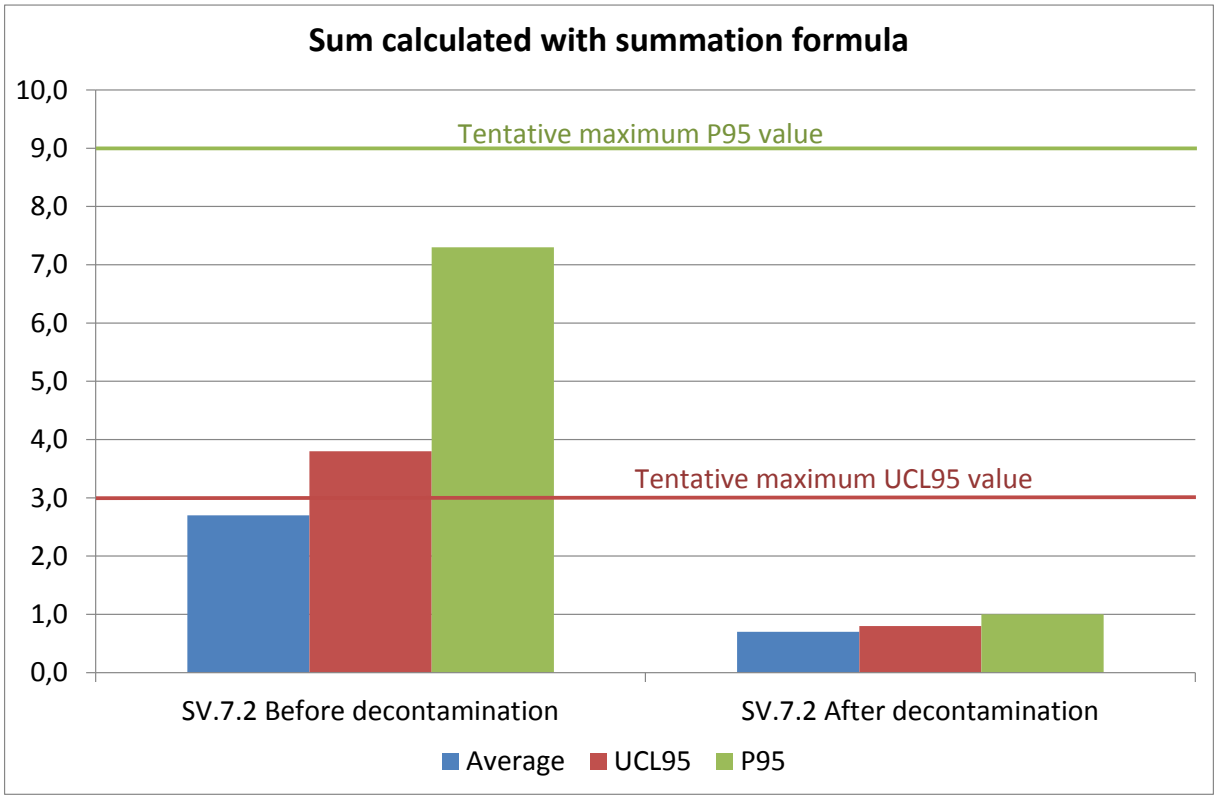

Figure 10: Contamination level of two sorting works system identities before and after decontamination

Grinding away a few millimeters of the concrete surface proved to be an effective way of reducing the contamination to a level well below the tentative clearance level for the average of all squares.

References

1. Karin von Kronhelm and Arne Larsson
   Radiological survey and mapping of hazardous waste
   Seminar on Decommissioning of nuclear facilities, Studsvik 14 – 16 September 2010
2. Radiation protection 113
   Recommended radiological protection criteria for the clearance of buildings and building rubble from the dismantling of nuclear installations
   European Commission: Recommendations of the group of experts set up under the terms of Article 31 of the Euratom Treaty

Appendix: Sampling Example

The Figure below shows examples of systematic and purely random sampling as well as stratified random sampling. It is believed that practitioners avoid random sampling because of its tendency to leave portions of the area unsampled. Stratified random sampling is a technique that avoids this disadvantage and at the same time opens up for good assessment of uncertainty.

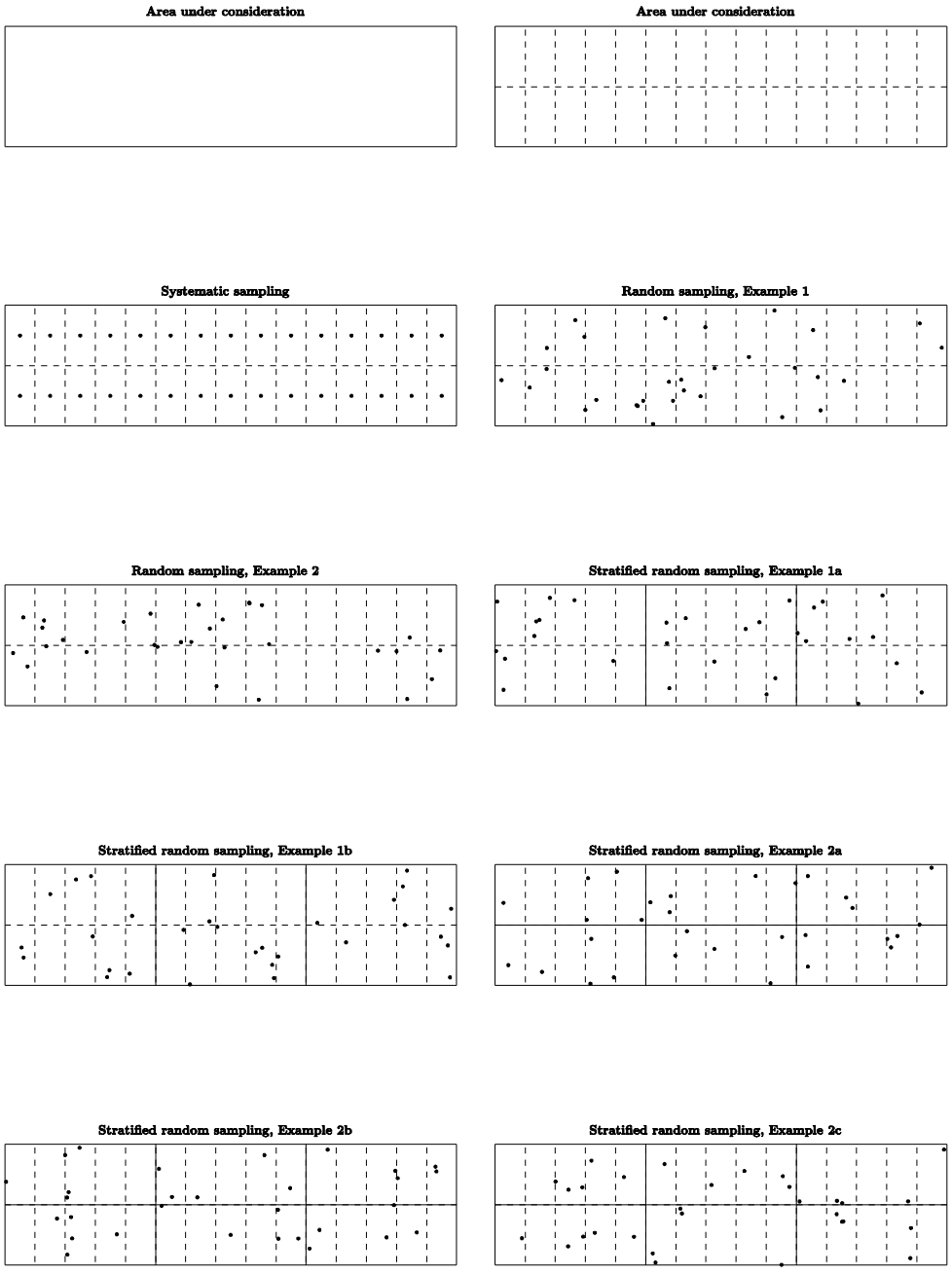

Figure: Examples of systematic, (purely) random and stratified random sampling in a rectangular area