

**Ranstad tailing site:  
Basic Characteristics and Evaluation of Restoration Options**

Restoration Strategies for Radioactively Contaminated  
Sites and their Close Surroundings  
RESTRAT

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## **1 Terms of reference**

This report is submitted as Technical Deliverable ‘TD10’ against the requirements of Work Package 1.1 for the Restoration Strategies for Radioactive Sites and their Close Surroundings, RESTRAT, project.

The RESTRAT project, which is funded by the European Commission under the Nuclear Fission Safety Programme, has the overall objective of developing generic methodologies for ranking restoration techniques as a function of contamination and site characteristics. The development of this generic methodology is based on an analysis of existing remediation methodologies and contaminated sites, and is structured in the following steps:

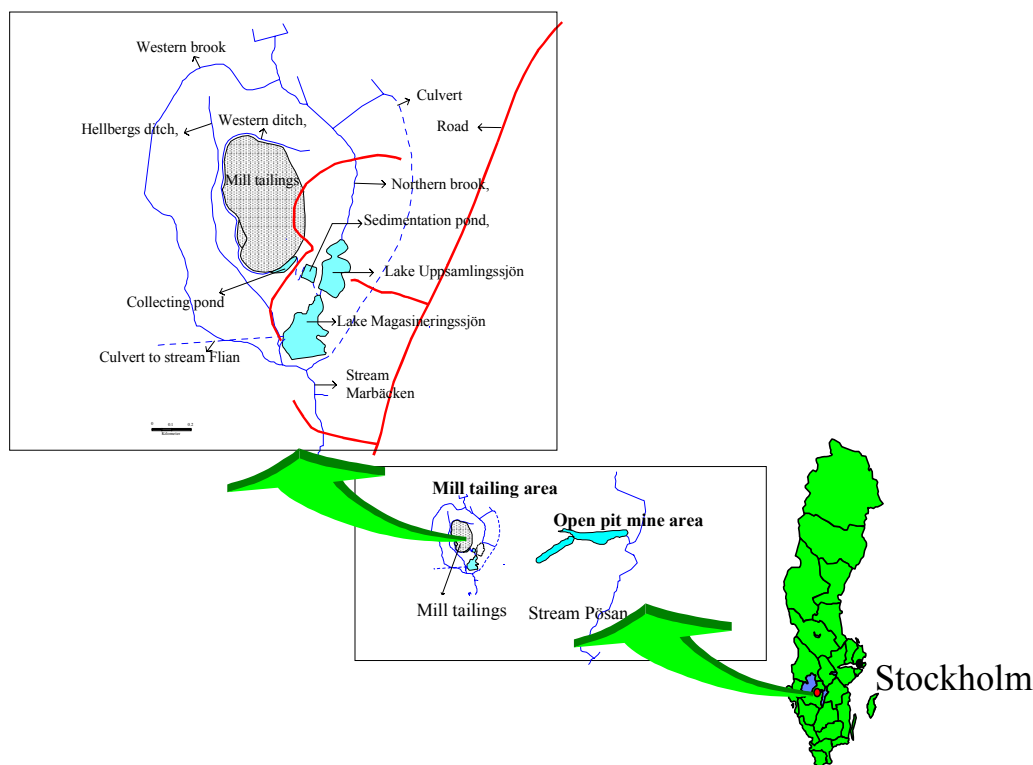
- 1 characterise relevant contaminated sites;
- 2 identify and characterise relevant restoration techniques;
- 3 assess the radiological impact;
- 4 develop and apply a selection methodology for restoration options;
- 5 formulate generic conclusions and development of a manual.

This work package, which is jointly funded by the Swedish Radiation Protection Institute, is concerned with the dose assessments for the Ranstad site and subsequent impact of restoration techniques. The aims of this Work Package are to:

- 1 describe the main geographic, hydrographic and geological features of the site;
- 2 describe the local human activities;
- 3 describe the major sources of radioactive contamination;
- 4 identify possible restoration options;
- 5 assess the impacts of the radioactive contamination and the effect of each restoration option;
- 6 evaluate and rank each remediation option, in terms of the suitability for the Ranstad site.

## 2 Introduction

The Ranstad Tailing Site is situated in the southern part of Sweden, in the Billingen-Häggum district, Figure 1. The tailing stem from a former uranium processing plant of AB Atomenergi, which operated on the uranium mined in a nearby open pit mine. Nowadays these plant processes filter resin from fuel fabrication at Västerås and waste from incineration handling of low-level radioactive waste at Studsvik.

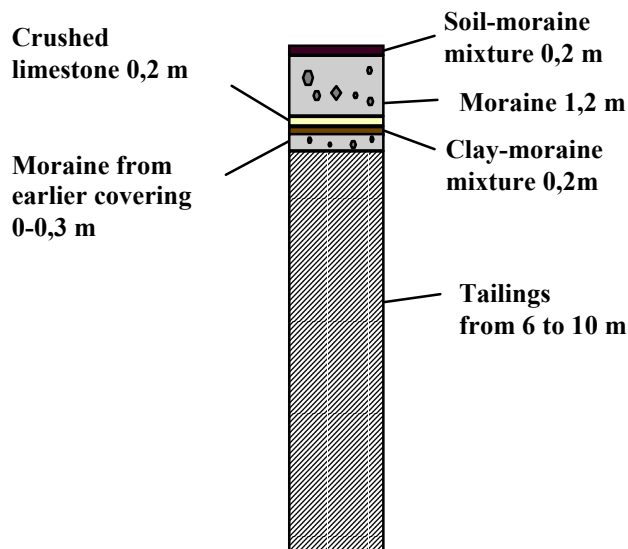


**Figure 1** Geographical location of the Ranstad tailing site and details of the mill tailing area.

The industrial facilities for the uranium mining and milling in Ranstad, Sweden were built between 1960 and 1965. Test operations (mining and ore processing) were carried out between 1965 and 1969 during which 1.5 million tonnes of alum shale were mined. About 215 tonnes of uranium oxide were extracted from the ore. Studsvik AB was responsible for the planning and performance of the remediation until 1991. Another company, AB SVAFO, a sister company to the Swedish Nuclear Fuel and Waste Management Company, was founded in 1992 and has since then been responsible for the completion of the remediation.

In 1984 the mining permit ceased and the planning for the remediation began at that time. The planning resulted in a remediation plan which was presented for the responsible county authority, Länsstyrelsen Skaraborgs län, in October 1988 (nowadays Länsstyrelsen Västra Götaland). After a comprehensive review the county administration presented the conditions for the remediation in January 1990. The content of the plan involved covering the mill tailing area with a multi-layer system (the dry depository) and filling the open pit mine with weathered shale and water (the wet depository). The objectives of the restoration work were that no maintenance work would be necessary in the future. An environmental control program was initiated before the restoration period. Environmental measurements have since then been carried out.

The former open pit mine, Lake Tranebärssjön is described in RESTRAT TD.13 (Stiglund, 1999). In the mill tailing area (see Figure 1) about  $10^6 \text{ m}^3$  of tailing have been deposited, covering an area of  $230\,000 \text{ m}^2$ . The tailing consists of crushed alum shale, leached slag, from the uranium mining as well as dams containing slimes from the uranium processing and from purification of the water. Remediation of the mill tailing included covering by a multi-layer system (see Figure 2).



**Figure 2** Cross-section of the mill tailing, showing the multi-layer covering system.

The mill tailing are shaped into stable slopes, which allow efficient drainage of the surface water.

### 3 General site characterisation

#### 3.1 Description of the area

##### 3.1.1 Geography and topography

The Ranstad area and the tailing site are situated in the southern part of Sweden, in the country of Västra Götaland, at the borderline between the communities of Skövde and Falköping. The location of the area is about 20 km south of the city of Skövde, in the Billingen –Häggum district next to the Billingen mountain.

##### 3.1.2 Geology and hydrogeology

The geological profile within the Ranstad area consists of moraine (5-8 metres in depth), underlayed by limestone (20-25 metres in depth), alum shale (23-24 metres in depth), sandstone (~30 metres) and the archaic rock. The main constituents of the Ranstad alum shale are shown in Table 1.

**Table 1 Main constituents in the alum shale of Ranstad**

Uranium	305 ppm
Organic substances	18 %
Sulphur	7 %
Aluminium	6 %
Potassium	4 %
Magnesium	0.5 %
Vanadium	750 ppm
Molybdenum	150 ppm
Nickel	200 ppm

The groundwater aquifers considered in the area are moraine, limestone and tailing. Boreholes connecting to the different aquifers are located on and around the tailing area. The groundwater levels are regularly sampled. Measurements of groundwater pressure show that the pressure of the tailing is higher than in the moraine and the groundwater pressure of the limestone considerable lower than in the moraine. This indicates a possible downward movement of the groundwater (Hörnsten *et al* 1977 and Magnusson *et al* 1998).

##### 3.1.3 Pedology

The soil layer consists mainly of moraine with high content of clay minerals (about 15%). The depth of the soil layer beneath the tailing area is 5-8 metres (median value 5.9 metres).

##### 3.1.4 Meteorology

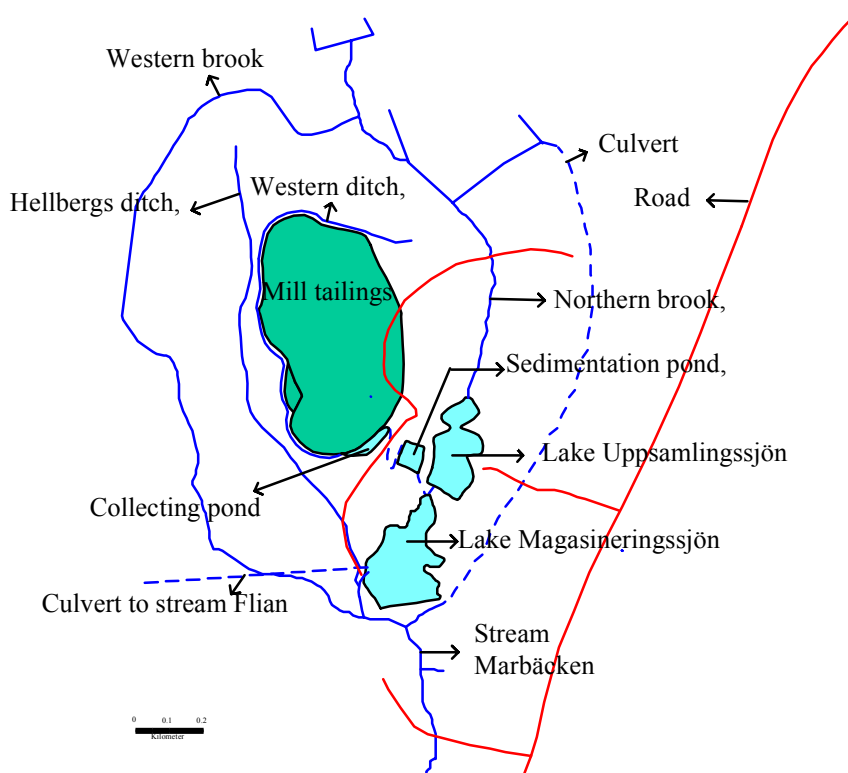
The meteorological data was supplied by the SMHI weather station of Skövde, see Table 2. The evapotranspiration is about 545 mm year<sup>-1</sup>.

**Table 2 Meteorological data for Skövde.**

Month	Normal temperature 1961-1990 °C	Rainfall 1961-1990 mm month <sup>-1</sup>
January	-2.8	48
February	-2.9	33
March	0.0	36
April	4.6	39
May	10.6	49
June	15.0	49
July	16.2	63
August	15.2	68
September	12.1	67
October	7.1	70
November	2.2	70
December	-2.3	54
Mean	6.3	54

### 3.1.5 Hydrology

The mill tailing are situated in an old discharge area with peat occurring in spots. Initially the Marbäcken stream flowed across the area (see Figure 2).



**Figure 2 Watercourses and Lakes of the mill tailing area.**

When the residues from the extracted alum shale were placed in the area, two lakes were formed; Lake Uppsamlingssjön and Lake Magasineringsjön. Lake Uppsamlingssjön was shaped in order to collect the leachate from the tailing area via the surrounding ditches, the Western ditch and the northern ditch. The water was then purified in a purification plant before entering a sedimentation pond (where sedimentation takes place) and, thereafter, discharged into Lake Magasineringsjön. Nowadays, the leachate-water is drained to the western ditch and the collecting pond, from which the water is pumped to the purification plant and sedimentation pond. Further on, the leachate-water flows over a triangular weir into the Lake Magasineringsjön. From the Lake Magasineringsjön the water is pumped via a culvert across Mount Billingen to the watercourses Flian and Slafsan which discharges into the River Hornborgaån, which finally discharges into Lake Hornborgasjön.

Flow rates of importance are presented in Table 3 below.

**Table 3 Flow rates.**

Streams	$\text{m}^3 \text{ year}^{-1}$ (1997)
Leachate, collecting ditch	1.2 E5
Marbäcken stream	8.2 E5
Water pumped to Flian	1.8 E5

The municipal authorities decided in 1997 environmental goals for a number of heavy metals in Lake Magasineringsjön. When the goals are reached during a period of three years in a row the purified water will be let out in its original course of the Marbäcken stream.

### 3.1.6 Population

#### Demography

The area is sparsely populated, with some detached farms in the near vicinity. Two small villages, Stenstorp (south-east of Ranstad) and Skultorp (north-east of the tailing site), are situated within five kilometres of Ranstad. Stenstorp inhabited by about 2000 people and Skultorp about 3500. Forest and pastureland mainly cover the area around the Ranstad site.

#### Habits

The critical group in the Ranstad area consists of farmers living in the neighbourhood. They consume locally produced meat and drink milk from cows locally farmed. The fish are captured in Lake Magasineringsjön. The drinking water is taken from the limestone aquifer beneath the tailing. Critical group characteristics are defined in Table 4. Data considered are typical for an average Swede.



**Table 4 Critical group consumption.**

Foodstuff	Consumption rate
Water (m <sup>3</sup> year <sup>-1</sup> )	0.73
Fish (kg year <sup>-1</sup> )	20
Milk (m <sup>3</sup> year <sup>-1</sup> )	0.33
Meat (kg year <sup>-1</sup> )	95

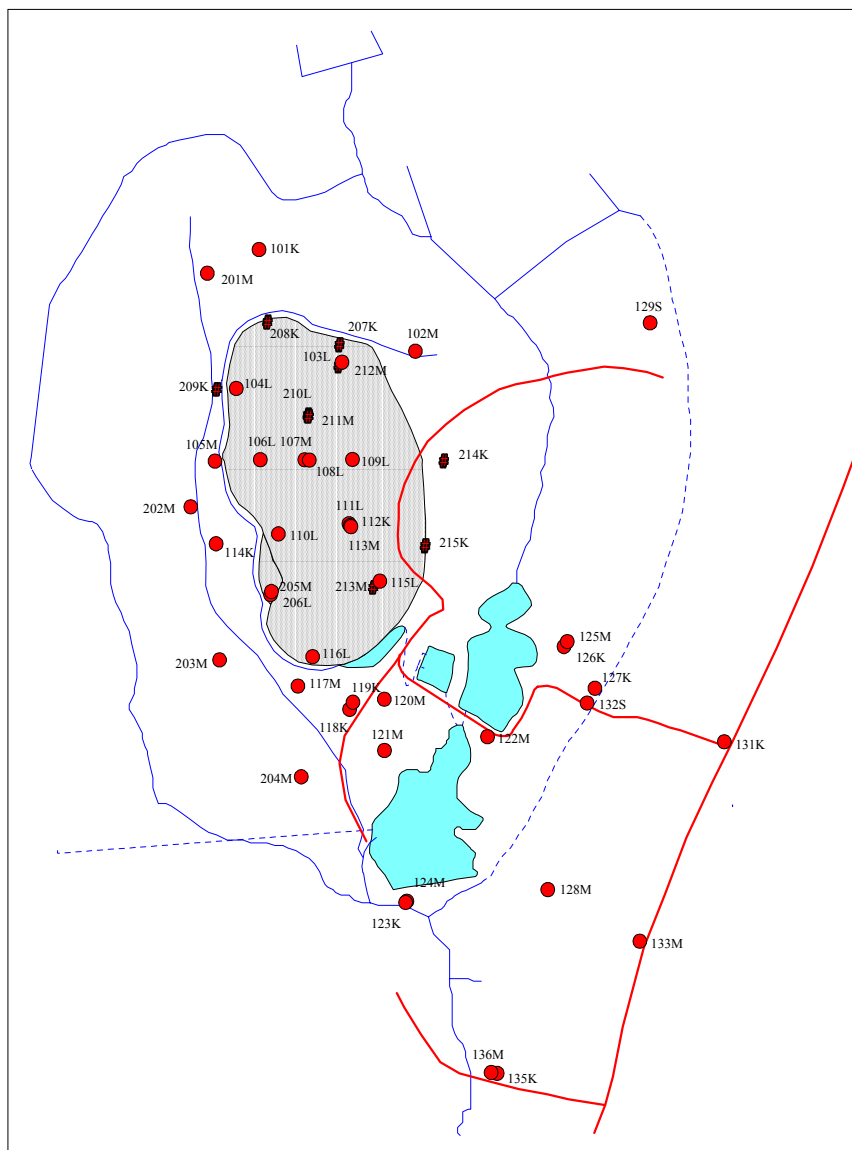
### Activities

Fish are released into Lake Magasineringsjön, by an active fishing club located in the area. Consumption of locally produced crops are not considered for the critical group, since the arable land around the Ranstad site is mainly used for grazing of cattle or for growing crops used as fodder for animals.

## 3.2 Physico-chemical characteristics

### 3.2.1 Aquatic phases

In order to carry out a dose assessment for the Ranstad tailing site it is necessary to describe the site in terms of a compartment system. The compartment structure (see Section 5.1) includes several sections of the hydrological system, all parts of which were characterised. Five compartments were involved, namely: ground waters from the tailing layer, the moraine layer, the limestone layer, surface waters from the collecting ditch on the west side of the tailing and from the so-called M-lake (Magasineringsjön) storage reservoir. There have been extensive analytical campaigns since 1965, with enforced activities after 1992. Most of the results are reported in (Sundblad *et al.*, 1996), which also contains the data sets related to Lake Tranebärssjön (see also Stiglund, 1999). The monitoring campaign has continued until the present, the results from 1996 and 1997 were available as spreadsheet files. From here on, references to samples always include the location of the boreholes, where the samples were taken from. A label consisting of three digits followed by a letter indicating the aquifer layer identifies all boreholes. For an exact location of the boreholes, also see Figure 3.



**Figure 3** Groundwater boreholes in the different aquifers: moraine-M, limestone-K and tailing-L.

Available primary (measured) data sets include:

- annual average values for pH, temperature, conductivity and a number of anion and cation concentrations for 16 surface and lake water sampling points
- metal concentrations in water samples from four wells
- metal concentrations in water samples from the three main aquifers of the tailing
- radium content in waters from three sampling points
- metal concentrations in water samples from 34 bore holes
- precipitation and temperature curves (1995 and long-time annual mean)

- annual variations in water discharge and pH at various stations (surface, lake and groundwater)
- annual variations in the contents of sulphate, iron, nickel, cadmium, aluminium, manganese, magnesium, calcium, and uranium at various stations (lake, surface- and groundwater).

Based on these data sets, other values were computed, such as the amount of transported metals per year. The analytical values relevant for the five compartments mentioned above were taken from this data pool, supplemented by some additional material from Studsvik. These values exhibit several general features:

- wide distributions of values, even for samples drawn at the same day from probe bore holes only 100 m apart (for example 109L and 111L samples from February 6, 1995)
- unusually high values for iron and aluminium, exceeding the saturation limit for many minerals of these elements. This is also valid, although to a lesser degree, for lead, nickel, manganese, cadmium and arsenic
- no analysis for anions in the groundwater layers
- there are no details available about the sampling, conditioning, filtering and analytical procedures applied in the analysis

Therefore, in August 1996, additional measurements were performed as part of the RESTRAT project to close gaps in the previous investigations, and to verify the accuracy of those measurements. The new results (for details, see Tables 5 to 9 below), together with the results from the previous sampling campaigns, were checked for consistency. The set of selected best values is listed in Table 5. Average values (MEAN) and standard deviations (STD) were calculated assigning equal weights to all listed values. Exceptions are aluminium and iron, where only the values from 1996 were taken into consideration. For these heavy metals, the older measurements clearly showed much too high concentrations, indicating strong oversaturation with respect to many minerals. Obviously those samples were not filtered properly and hence the analytical values incorporated finely-disperse and colloidal material. The values from filtered samples from 1996 show that both dissolved iron and aluminium only are trace components. The following selection criteria were applied:

- tailing layer: values from the FZR analysis and from bore hole 111L were averaged, with the exception of iron, aluminium, lead and thorium for which only the FZR analysis were used.
- moraine layer: values from bore hole 105M were used (105M is defined as the reference station for the moraine layer in Sundblad *et al.* (1996)), with the exception of iron, aluminium, thorium and all anions other than sulphate, for which only the FZR analysis were used.
- limestone layer: values from borehole 101K were averaged (101K is defined as reference station for the limestone layer in Sundblad *et al.* (1996)), with the exception of iron, aluminium and thorium, for which only the FZR analysis were used.
- Lake Magasineringsjön, the M-Lake: values from the FZR analysis and from the sampling point station 5 were averaged.
- Western Ditch: values from the sampling point station 2 were used.

The usage of anion concentrations for the moraine layer based on FZR analysis is an intermediate solution. These samples were drawn from boreholes drilled inside the tailing area, and therefore are more or less influenced by the overlaying tailing layer, i.e., the analytical values for the anions are not consistent with the values for the cations. Thus it is necessary to analyse new samples from the

reference borehole 105M. The redox potential has not ever been measured. Superscript <sup>1)</sup> indicates values assigned to the compartments due to speciation modelling with EQ3/6 (Wolery, 1995), based on the independent values for the redox couples NO<sub>3</sub><sup>-</sup> / NO<sub>2</sub><sup>-</sup> / NH<sub>4</sub><sup>+</sup>; <sup>2)</sup> mark values set arbitrarily to define an oxidising state, there is no information available about the real redox potential at the moment

**Table 5 Selected best set of analytical values for the Ranstad Tailing Site (mol/L).**

Compartment: Abbreviation:	Tailing L		Moraine M		Limestone K		M-Lake S		W-Ditch D	
Component:	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
F- PO <sub>4</sub> <sup>3-</sup>	1.088E-04 1.959E-06	3.70E-05 1.03E-06	< 2.1E-05	2.47E-05 4.93E-05	7.106E-06 5.328E-07	2.61E-06 5.25E-07	3.159E-08		1.474E-07	
NO <sub>3</sub> <sup>-</sup>	1.188E-04	8.48E-05	1.097E-05	7.14E-05	7.139E-05		1.840E-05	7.42E-06	8.967E-06	
NO <sub>2</sub> <sup>-</sup>	3.189E-06	1.77E-06	< 1.1E-05	1.78E-07	2.856E-07	2.02E-07	2.826E-07		3.043E-07	
NH <sub>4</sub> <sup>+</sup>	4.450E-04	2.30E-05		3.21E-05	7.139E-06		1.663E-05		1.502E-04	
SO <sub>4</sub> <sup>2-</sup>	2.293E-02	2.23E-03	2.567E-04	7.30E-03	5.350E-04	7.29E-05	5.815E-03	5.65E-04	1.028E-02	7.63E-04
CO <sub>3</sub> <sup>2-</sup>	3.584E-03	1.10E-03	3.715E-03	9.30E-03	2.991E-03	5.79E-05	1.593E-03	1.35E-03	4.835E-04	
Cl <sup>-</sup>	5.639E-04	6.47E-05	3.798E-04	2.68E-04	3.244E-04	1.99E-05	2.191E-04	8.14E-06	1.912E-04	
SiO <sub>2</sub>	6.834E-05	1.28E-05	4.593E-04	7.05E-05	2.464E-04	3.51E-05	3.270E-05	6.19E-06	2.154E-04	
K <sup>+</sup>	1.175E-03	8.91E-05	3.363E-05	8.14E-06	3.775E-05	9.18E-06	3.954E-04	2.59E-05	9.962E-04	1.14E-04
Na <sup>+</sup>	8.647E-04	4.44E-05	2.736E-04	9.66E-05	2.913E-04	2.26E-05	1.139E-03	4.26E-04	5.850E-04	2.15E-05
Ca <sup>2+</sup>	1.075E-02	2.15E-03	1.643E-03	3.62E-04	1.696E-03	3.17E-04	5.291E-03	1.05E-04	9.294E-03	1.59E-04
Mg <sup>2+</sup>	1.038E-02	3.33E-04	1.446E-04	3.46E-05	2.092E-04	2.85E-05	7.634E-04	6.75E-05	2.580E-03	1.75E-04
Fe	3.581E-07		3.581E-07		3.581E-07					
Al <sup>3+</sup>	1.223E-07	5.77E-08	2.038E-07		7.042E-08		1.112E-07	4.50E-07		
Zn <sup>2+</sup>	4.590E-07	4.28E-07	3.228E-06	4.50E-06	7.158E-08	3.91E-08	1.652E-07	1.62E-07	2.983E-07	
U	1.004E-06	2.36E-07	5.128E-09	4.57E-09	4.887E-09	1.15E-09	3.033E-08	1.02E-09	1.012E-07	
Th	1.293E-09		3.232E-09		3.080E-07		1.293E-09			
Pb <sup>2+</sup>	1.977E-08	3.13E-08	5.772E-08	7.26E-08	8.517E-09	5.85E-09	2.823E-09		3.224E-09	
Ni <sup>2+</sup>	6.275E-07	1.96E-07	5.182E-07	6.57E-07	7.491E-08	9.13E-09	1.337E-07	1.29E-07	1.755E-06	
Mn <sup>2+</sup>	8.670E-05	2.98E-05	5.646E-06	5.45E-06	7.077E-06	2.72E-06	8.513E-06	5.38E-06	6.888E-05	
Cd <sup>2+</sup>	4.183E-09	8.83E-10	1.299E-09	1.43E-09	3.034E-10	1.12E-10	3.096E-09		3.567E-09	
As	2.456E-08	1.96E-08	1.615E-08	1.38E-08	1.041E-08	2.58E-09	3.377E-08	5.10E-09	5.112E-08	
pH	7.46	0.15	6.93		7.85	0.12	7.80		6.88	
T (in °C)	8.8		9.0		9.0		7.9		8.5	
Eh (in mV)	346		800		800		318		374	

During the analytical campaign in 1996 samples were taken by Studsvik Eco & Safety AB (with the pH determined *in-situ*) and shipped to FZ Rossendorf, where the analysis was performed. Tables 6 to 9 summarise the analytical results for these samples. The samples were analysed twice, first without further treatment (columns A), and second after filtering, done in three steps for 450, 100, and 15 nm particle size (columns B). Columns labelled with MW give the molecular weight of the atoms or ionic units from column one, n.d. stands for “not determined”. Upper limit values denote that the analytical value was below the respective detection limit. The methods given in the last column are: IC = Ion Chromatography, ICP-MS = Inductively Coupled Plasma - Mass Spectrometry, F-AAS = Flame - Atom Adsorption Spectrometry. Radium (with radium-223 and radium-224 being negligible) and thorium (determined from equilibrium with actinium-228, other thorium-nuclides being negligible) were analysed with gamma-Spectrometry. The measured values are given in Bq kg<sup>-1</sup>.

**Table 6 Analysis of water from the tailing aquifer of the Ranstad Tailing Site.**

Location:	111L (A)	111L (B)	111L (A)	111L (B)	MW	111L (A)	111L (B)	111L (A)	111L (B)	Method
Unit:	µg / L	µg / L	µg / L	µg / L	g/mol	mol / L	mol / L	mol / L	mol / L	
Date:	25.6.1996		7.10.1996							
PO <sub>4</sub> <sup>3-</sup>		< 2000	< 2000	< 2000	94.971	< 2.1E-05	< 2.1E-05	< 2.1E-05		IC
NO <sub>3</sub> <sup>-</sup>		1780	12000	11700	62.005	2.871E-05	1.935E-04	1.887E-04		IC
NO <sub>2</sub> <sup>-</sup>		< 500	3500	3900	46.0055	< 1.1E-05	< 1.1E-05	< 1.1E-05		IC
SO <sub>4</sub> <sup>2-</sup>		1890000	2300000	2250000	96.058	1.968E-02	2.394E-02	2.342E-02		IC
HCO <sub>3</sub> <sup>-</sup>		234000	160000	174000	61.017	3.835E-03	2.622E-03	2.852E-03		IC
Cl <sup>-</sup>		16600	21600	21100	35.453	4.682E-04	6.093E-04	5.952E-04		IC
Si	2170	2320	2010	1630	28.086	7.726E-05	8.260E-05	7.157E-05	5.804E-05	ICP-MS
K <sup>+</sup>	42000	42000	47800	48600	39.098	1.074E-03	1.074E-03	1.223E-03	1.243E-03	F-AAS
Na <sup>+</sup>	19200	18700	19800	20500	22.99	8.351E-04	8.134E-04	8.612E-04	8.917E-04	F-AAS
Ca <sup>2+</sup>	340000	334000	480000	460000	40.08	8.483E-03	8.333E-03	1.198E-02	1.148E-02	ICP-MS
Mg <sup>2+</sup>	243000	260000	239000	253000	24.305	9.998E-03	1.070E-02	9.833E-03	1.041E-02	F-AAS
Fe	470	20	6200	< 0.1	55.847	8.416E-06	3.581E-07	1.110E-04	< 1.8E-09	F-AAS
Al <sup>3+</sup>	7.8	2.2	218	4.4	26.9815	2.891E-07	8.154E-08	8.080E-06	1.631E-07	ICP-MS
Zn <sup>2+</sup>	2.7	2	41	57.9	65.38	4.130E-08	3.059E-08	6.271E-07	8.856E-07	ICP-MS
U	244	243	215	181	238.03	1.025E-06	1.021E-06	9.032E-07	7.604E-07	ICP-MS
Th	n.d.	n.d.	0.8	0.3	232.0381			3.448E-09	1.293E-09	ICP-MS
Pb <sup>2+</sup>	0.5	0.3	5.2	0.4	207.2	2.413E-09	1.448E-09	2.510E-08	1.931E-09	ICP-MS
Ni <sup>2+</sup>	30	25	61.7	37.5	58.7	5.111E-07	4.259E-07	1.051E-06	6.388E-07	ICP-MS
Mn <sup>2+</sup>	5330	4780	5040	3120	54.938	9.702E-05	8.701E-05	9.174E-05	5.679E-05	ICP-MS
Cd <sup>2+</sup>	0.4	0.4	n.d.	n.d.	112.41	3.558E-09	3.558E-09			ICP-MS
As	0.8	0.8	1.8	< 2	74.922	1.068E-08	1.068E-08	2.402E-08	< 2.7E-08	ICP-MS
Ra-226		2.84		3.40			3.43E-13		4.11E-13	Gamma
Th-232		0.78		0.34			8.28E-07		3.61E-07	Gamma

The pH value was between 7.2 and 7.5 *in-situ*, between 7.07 and 7.15 before filtration and between 7.98 and 8.14 after filtration. The content of suspended material was determined to be 20.37 mg g<sup>-1</sup>. The temperature of the sample was 8.8°C.

**Table 7 Analysis of water from the moraine aquifer of the Ranstad Tailing Site.**

Location:	113M (A)	113M (B)	113M (A)	113M (B)	MW	113M (A)	113M (B)	113M (A)	113M (B)	Method
Unit:	µg / L	µg / L	µg / L	µg / L	g / mol	mol / L	mol / L	mol / L	mol / L	
Date:	25.6.1996		7.10.1996							
PO <sub>4</sub> <sup>3-</sup>		< 2000	< 2000	< 2000	94.971	< 2.1E-05	< 2.1E-05	< 2.1E-05	< 2.1E-05	IC
NO <sub>3</sub> <sup>-</sup>		680	< 1000	< 1000	62.005	1.097E-05	< 1.6E-05	< 1.6E-05	< 1.6E-05	IC
NO <sub>2</sub> <sup>-</sup>		< 500	< 1000	< 1000	46.0055	< 1.1E-05	< 1.1E-05	< 1.1E-05	< 1.1E-05	IC
SO <sub>4</sub> <sup>2-</sup>		2565000	3000000	3350000	96.058	2.670E-02	3.123E-02	3.487E-02	3.487E-02	IC
HCO <sub>3</sub> <sup>-</sup>		192000	240000	248000	61.017	3.147E-03	3.933E-03	4.064E-03	4.064E-03	IC
Cl <sup>-</sup>		12600	13900	13900	35.453		3.554E-04	3.921E-04	3.921E-04	IC
Si	6890	5910	8230	6130	28.086	2.453E-04	2.104E-04	2.930E-04	2.183E-04	ICP-MS
K <sup>+</sup>	209000	212000	256000	271000	39.098	5.346E-03	5.422E-03	6.548E-03	6.931E-03	F-AAS
Na <sup>+</sup>	50100	54100	64500	70200	22.99	2.179E-03	2.353E-03	2.806E-03	3.054E-03	F-AAS
Ca <sup>2+</sup>	320000	327000	415000	410000	40.08	7.984E-03	8.159E-03	1.035E-02	1.023E-02	ICP-MS
Mg <sup>2+</sup>	293000	234000	380000	375000	24.305	1.206E-02	9.628E-03	1.563E-02	1.543E-02	F-AAS
Fe	43500	20	102000	< 100	55.847	7.789E-04	3.581E-07	1.826E-03	< 1.8E-06	F-AAS
Al <sup>3+</sup>	14.4	2.3	633	8.7	26.9815	5.337E-07	8.524E-08	2.346E-05	3.224E-07	ICP-MS
Zn <sup>2+</sup>	20	1.6	40.5	39.2	65.38	3.059E-07	2.447E-08	6.195E-07	5.996E-07	ICP-MS
U	81	68	110	31.7	238.03	3.403E-07	2.857E-07	4.621E-07	1.332E-07	ICP-MS
Th	n.d.	n.d.	1.3	0.2	232.0381			5.603E-09	8.619E-10	ICP-MS
Pb <sup>2+</sup>	0.4	0.2	1.4	1.3	207.2	1.931E-09	9.653E-10	6.757E-09	6.274E-09	ICP-MS
Ni <sup>2+</sup>	96	76	134	123	58.7	1.635E-06	1.295E-06	2.283E-06	2.095E-06	ICP-MS
Mn <sup>2+</sup>	8340	8210	8580	6710	54.938	1.518E-04	1.494E-04	1.562E-04	1.221E-04	ICP-MS
Cd <sup>2+</sup>	0.1	0.08	n.d.	n.d.	112.41	8.896E-10	7.117E-10			ICP-MS
As	0.7	0.6	7.2	< 2	74.922	9.343E-09	8.008E-09	9.610E-08	< 2.7E-08	ICP-MS
Ra-226		n.d.		1.77					2.14E-13	Gamma
Th-232		n.d.		0.16					1.70E-07	Gamma

The pH value was between 6.4 and 6.6 *in-situ*, 6.14 before filtration, and between 7.09 and 7.27 after filtration. The content of suspended material was determined to be 139.62 mg g<sup>-1</sup>. The temperature of the sample was 9.0°C.

**Table 8 Analysis of water from the limestone aquifer of the Ranstad Tailing Site.**

Location:	112K (A)	112K (B)	112K (S)	MW	112K (A)	112K (B)	112K (S)	Method
Unit:	µg / L	µg / L	µg / L	g / mol	mol / L	mol / L	mol / L	
Date:	23.6.1996							
PO <sub>4</sub> <sup>3-</sup>		< 2000	< 2000	94.971		< 2.1E-05	< 2.1E-05	IC
NO <sub>3</sub> <sup>-</sup>		3050	3050	62.005		4.919E-05	4.919E-05	IC
NO <sub>2</sub> <sup>-</sup>		< 500	< 500	46.0055		< 1.1E-05	< 1.1E-05	IC
SO <sub>4</sub> <sup>2-</sup>		390000	390000	96.058		4.060E-03	4.060E-03	IC
HCO <sub>3</sub> <sup>-</sup>		261000	261000	61.017		4.277E-03	4.277E-03	IC
Cl <sup>-</sup>		2050	2050	35.453		5.782E-05	5.782E-05	IC
Si	3190	3140	3000	28.086	1.136E-04	1.118E-04	1.068E-04	ICP-MS
K <sup>+</sup>	80000	79000	92800	39.098	2.046E-03	2.021E-03	2.374E-03	F-AAS
Na <sup>+</sup>	24800	23900	30800	22.99	1.079E-03	1.040E-03	1.340E-03	F-AAS
Ca <sup>2+</sup>	233000	226000	303000	40.08	5.813E-03	5.639E-03	7.560E-03	ICP-MS
Mg <sup>2+</sup>	168000	158000	145000	24.305	6.912E-03	6.501E-03	5.966E-03	F-AAS
Fe	630	20	550	55.847	1.128E-05	3.581E-07	9.848E-06	F-AAS
Al <sup>3+</sup>	5.4	1.9	n.d.	26.9815	2.001E-07	7.042E-08		ICP-MS
Zn <sup>2+</sup>	6.4	1	n.d.	65.38	9.789E-08	1.530E-08		ICP-MS
U	83	83	73.7	238.03	3.487E-07	3.487E-07	3.096E-07	ICP-MS
Pb <sup>2+</sup>	0.5	0.1	n.d.	207.2	2.413E-09	4.826E-10		ICP-MS
Ni <sup>2+</sup>	65	50	58.8	58.7	1.107E-06	8.518E-07	1.002E-06	ICP-MS
Mn <sup>2+</sup>	2120	1520	2200	54.938	3.859E-05	2.767E-05	4.005E-05	ICP-MS
Cd <sup>2+</sup>	0.6	0.5	n.d.	112.41	5.338E-09	4.448E-09		ICP-MS
As	0.8	0.6	< 5	74.922	1.068E-08	8.008E-09	< 6.7E-08	ICP-MS
Ra-226		1.6				1.93E-13		Gamma
Th-232		0.29				3.08E-07		Gamma

The pH value was 6.3 *in-situ*, 6.79 before filtration, and 7.53 after filtration. The content of suspended material was determined to be 45.25 mg g<sup>-1</sup>. The temperature of the sample was 9.0°C.

**Table 9 Analysis of water from the M-Lake at the Ranstad Tailing Site.**

Sample:	A	B	MW	A	B	Method
Unit:	µg / L	µg / L	g / mol	mol / L	mol / L	
Date:	26.11.1996					
PO <sub>4</sub> <sup>3-</sup>	< 2000	< 2000	94.971	< 2.1E-05	< 2.1E-05	IC
NO <sub>3</sub> <sup>-</sup>	1500	1300	62.005	2.419E-05	2.097E-05	IC
NO <sub>2</sub> <sup>-</sup>	< 1000	< 1000	46.0055	< 2.2E-05	< 2.2E-05	IC
SO <sub>4</sub> <sup>2-</sup>	560000	630000	96.058	5.830E-03	6.559E-03	IC
HCO <sub>3</sub> <sup>-</sup>	150000	139000	61.017	2.458E-03	2.278E-03	IC
Cl <sup>-</sup>	7600	7600	35.453	2.144E-04	2.144E-04	IC
Si	720	1045	28.086	2.564E-05	3.721E-05	ICP-MS
K <sup>+</sup>	16100	16440	39.098	4.118E-04	4.205E-04	F-AAS
Na <sup>+</sup>	34700	34620	22.99	1.509E-03	1.506E-03	F-AAS
Ca <sup>2+</sup>	208000	211200	40.08	5.190E-03	5.269E-03	ICP-MS
Mg <sup>2+</sup>	16800	17620	24.305	6.912E-04	7.250E-04	F-AAS
Al <sup>3+</sup>	n.d.	3	26.9815		1.112E-07	ICP-MS
Zn <sup>2+</sup>	1.6	22.4	65.38	2.447E-08	3.426E-07	ICP-MS
U	7.1	7.5	238.03	2.983E-08	3.151E-08	ICP-MS
Th	< 0,05	0.3	232.0381	< 2.2E-10	1.293E-09	ICP-MS
Ni <sup>2+</sup>	2.5	n.d.	58.7	4.259E-08		ICP-MS
Mn <sup>2+</sup>	373	231	54.938	6.789E-06	4.205E-06	ICP-MS
As	2.8	n.d.	74.922	3.737E-08		ICP-MS

The pH value was 7.8 *in-situ*, 8.09 before filtration, and 8.26 after filtration. The content of suspended material was not determined. The temperature of the sample was 7.3°C.

A critical review of the selected data given in Table 5 shows that for most major anions, as well as for cations the analytical values have reasonable standard deviations (if available). Remarkable exceptions are the content of zinc, manganese and aluminium. No *in-situ* determinations of the redox state or measurements of the oxygen content in the water are available. Therefore, the only way to derive at least estimated values for the redox potential in the various waters was to model speciation and to compute Eh from the concentrations of the redox pairs NO<sub>3</sub><sup>-</sup>/NH<sub>4</sub><sup>+</sup> and NO<sub>2</sub><sup>-</sup>/NH<sub>4</sub><sup>+</sup>. This gave mean redox potentials of 346 mV, 318 mV and 374 mV for the tailing layer, lake Magasineringsjön (the M-lake) and the western ditch, respectively. This means slightly reducing conditions, as to be expected from water in contact with reducing minerals like pyrite, and a significant amount of organic matter. Due to a lack of appropriate analytical data for the other two aquifers, such computations could not be made for them. Until better information is available, oxidising conditions with a Eh of about 800 mV are assumed.

Since sulphates of magnesium and calcium dominate the water tables inside the tailing and moraine layers (also the pond waters), the limestone layer mainly contains carbonate water with both carbonates. The moraine layer in particular contains significant amounts of manganese and nickel. There is a pH gradient from the pond waters downwards through the tailing and moraine layers until the limestone aquifer.



From the conclusions above, several tasks needed to be carried out in the future can be deduced as:

- The sampling and transport procedure must be improved.
- Anion concentrations in the moraine layer have to be determined (from new samples).
- *In-situ* analysis for Eh should be performed.
- Correlation of analytical data with time (general trends and seasonal fluctuations) should be tested. Possibly the system is still far away from any steady-state situation, not to mention internal thermodynamic equilibrium.
- Correlation of analytical data with rainfall and temperature should be examined.
- A check for cross-correlation of analytical data of different elements would also be helpful.

### 3.2.2 Solid phases

The characterisation of the relevant solid phases is not as satisfactory as the characterisation of the aqueous phase. There are only rather general mineralogical investigations for this site published, which are supplemented by some elementary analysis of the moraine and tailing layer, of sediments of the western ditch and of Lake Magasineringsjön, the M-lake; the latter two being only fragmentary. From the available data, and speciation modelling based on them, the following conclusions can be drawn:

- the tailing layer is built from leached alum shale, mostly consisting of quartz, illite, and feldspars, with a significant content of pyrite (13%) and organics (22%).
- the moraine layer is similar in its composition to the tailing layer (but with lower organic content); mainly consisting of quartz sands and aluminosilicates.
- the limestone layer is naturally dominated by limestone.
- the sediments of Lake Magasineringsjön, the M-lake, and the western ditch can not be properly characterised at present.

Analysis is complicated by a considerable content of organic matter of various origins and in different states of degradation. If possible, further investigations should be performed to specify a more detailed description of the mineralogy of the site.

### 3.3 Radiological characteristics

The mill tailing area is not considered to be a radiological problem, even though the Swedish Radiation Protection Agency has decided that uranium and radium-226 should be measured four times a year, at two different places within the area. The places are at the station "the water lock" in the southern part of the tailing area (this station drains the whole mill tailing area) and at station 5 in Lake Magasineringsjön, the M-lake. The results of the measurements of radium-226 during the last three years are shown in Table 10.

**Table 10** Content of radium-226 in water from the tailing area.

Year and month	Leachate water, station 2A, mBq/L	Lake Magasineringsjön, station 5, mBq/L
1995-03	<32	<1.4
1995-07	<25	0.6
1995-10	9.1	3.8
1995-12	<3.9	<4.9
1996-03	-	<9.4
1996-07	-	4.1
1996-12	<1.9	<2.6
1997-01	<19	<2.6
1997-05	-	<3.3
1997-10	<16	7.5
1997-11	-	<4.8

### 3.3.3 Source term

The contaminants in the water are not only radionuclides, like uranium-238, but there are also significant levels of manganese and nickel. This implies that any risk assessment must include classical chemical-toxic effects as well as radiological ones. The source terms, which represents the initial concentration, are shown in Table 11.

**Table 11** Inventory at the Ranstad mill-tailing site.

Contaminant	kg
Uranium, U	1.8E5
Nickel, Ni	3.6E5
Manganese, Mn	3.1E6

### 3.3.4 Discharge/Effluents

The leachate from the tailing area as well as the subsurface water is being collected in a ditch surrounding the tailing, the Western ditch (Västra diket). Since the covering of the mill tailing during the years 1991-1992, the content of weathered minerals in the leachate has decreased. This is due to the almost oxygen-free environment, which has been established in the tailing. The infiltration and the oxygen content are measured continuously in the tailing. The measurements have shown that the sealing layer is almost impenetrable for oxygen. When it comes to the infiltration rate, the sealing layer fulfils the requirements of the highest permitted permeability through the sealing layer.

### 3.3.5 Contamination

The contamination that might occur will take place in the watercourses downstream the mill tailing area, that is the recipient Lake Magasineringsjön, the Marbäcken, Pösan and Slafsan streams, the River Hornborgaån or Lake Hornborgasjön. When the environmental goals (see Section 3.1.5 above) are fulfilled for Lake Magasineringsjön the water will discharge directly into its original flow, the

Marbäcken stream, instead of being pumped via the culvert across the Mount Billingen. The water will then flow in the same watercourses as described above. Until the environmental goals are fulfilled, the water from Lake Magasineringsjön is pumped across Mount Billingen and then discharged into the Flån, Slafsån streams, River Hornborgån and finally into Lake Hornborgsjön.

Lake Hornborgsjön is a restored lake, and is protected against any influence by environmental laws. The lake habits many species of birds, especially crane. As both water-flow directions (across Mount Billingen or via the Marbäcken creek) end up in Lake Hornborgsjön, it is of great importance that no contamination occurs in the watercourses.

#### 4 Restoration options

In order to remediate mill tailing, different restoration techniques can be considered. In the case of Ranstad mill-tailing site, three different categories of remediation techniques have been examined, containment, immobilisation and separation. In this study remediation of the site already has been carried out in order to make a comparison different techniques are considered in the assessment.

Containment reduces the amount of infiltrating water and the entrance of oxygen into the tailing. It is the percolating water together with oxygen that governs the weathering processes in the tailing. If the weathering processes stop, the amount of contaminants leaching from the tailing will be significantly reduced.

For the Ranstad tailing site two different types of capping have been considered. The first one consisting of 0.5 m moraine, which was covering the tailing before the remediation started, and another one consisting of 1.6 m of different layers (see Section 2), was actually performed in 1991-92.

Immobilisation is a technique where the aim is to reduce the mobility and solubility of contaminants. This can be done either by injecting solidifying material into the tailing (physical immobilisation), or by injecting immobilising reagents (chemical immobilisation). Since these methods would considerably reduce the leakage from the tailing, they have been included in this study.

Separation techniques are useful in order to separate the contaminants from the tailing to a concentrated solution. Both physical and chemical separation can be used for this purpose. Even though such methods are not likely to be used when large amounts are to be separated, due to high costs, these techniques has been considered for the Ranstad tailing site.

The remediation techniques which are available for treating the site are described in Technical Deliverable 3+4 (Zeevaert and Bousher, 1998). The restoration option valid and decontamination factors used for Ranstad tailing site are summarized in Table 12.

**Table 12 Site specific values (decontamination factors-Df) for the performance of remediation techniques appropriate to the Ranstad mill-tailing site.**

Restoration option	Df-factor U	Df-factor Ni	Df-factor Mn
A No remediation	-	-	-
C1 Physical separation	3 (1-5)	3 (1-5)	2 (1-4)
D1 Chemical separation	5 (3-7)	5 (3-7)	3 (1-5)
E1 Capping 0.5m	Infiltration reduced with a factor of 0.4	Infiltration reduced with a factor of 0.4	Infiltration reduced with a factor of 0.4
E2 Capping 1.6m	Infiltration reduced with a factor of 0.67	Infiltration reduced with a factor of 0.67	Infiltration reduced with a factor of 0.67
F2 Physical immobilisation	20 (5-25)	20 (5-25)	10 (5-25)
G2 Chemical immobilisation	30 (5-50)	30 (5-50)	20 (5-50)

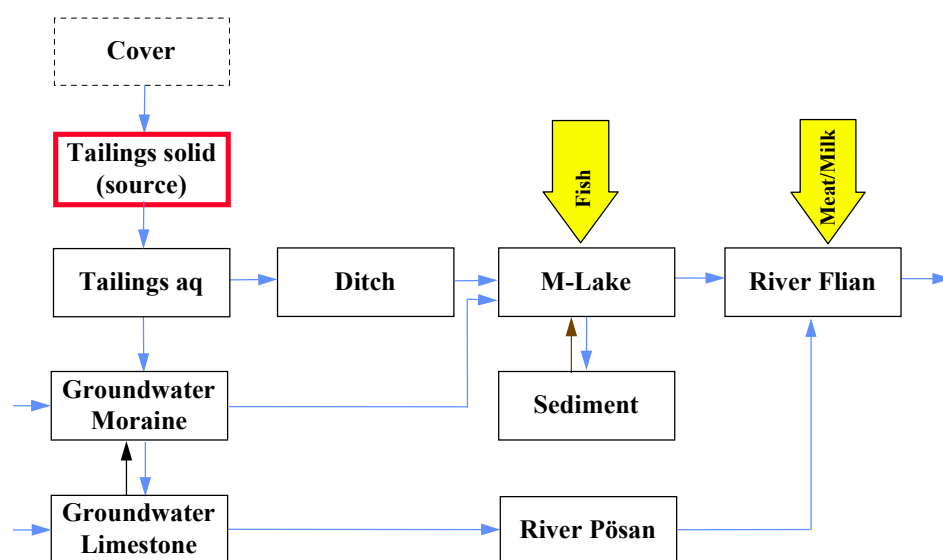
## 5 Radiological impact assessments

To demonstrate a generic approach for evaluating effects of different restoration options, a dose assessment model was developed for the Ranstad tailing site. Individual doses to average members of a critical group and committed collective doses as a measure of the total health detriment are calculated.

The contaminants are not only radionuclides, i.e. uranium-238, but there is also a significant level of manganese and nickel. Therefore, any risk assessment should include chemical-toxically effects too.

The dose assessment model consists of a compartment system which describes the Ranstad tailing site (see Figure 4). The compartment scheme for the Ranstad tailing site is based on site information in Stiglund (1999).

### 5.1 Compartment scheme



**Figure 4** Compartment scheme for the Ranstad tailing site.

The leachate from the tailing is transported both to a surrounding ditch and down into the moraine underneath the tailing. In the moraine the leachate is diluted and transported further to Lake Magasineringsjön. Some fraction of the leachate even reaches the limestone aquifer.

Each transfer coefficient can describe several more or less complicated processes. For each major compartment the following processes are considered for the turnover of radionuclides in the model for the Ranstad tailing site.

---

Compartment	Processes
Water column	Sedimentation of particles
Sediment	Resuspension
Groundwater	Transfer to deeper groundwater and surface water

---

Since the objective of the RESTRAT project is to show how different restoration options affect the dose to public and workers, the focus has not been to make detailed studies of all processes considered. Simplifications have been made both concerning the number of compartments used and details in the transport processes.

## 5.2 Critical groups and exposure pathways

The critical group, concerned with individual dose, should by definition consist of a real or fictitious group of individuals, which due to their location and living habits receive the highest exposure. At the Ranstad tailing site the critical group are farmers living in the neighbourhood. They consume locally produced meat and drink milk from cows. The fish is captured in the M-lake. The drinking water is taken from the limestone aquifer underneath the tailing. Remediation workers are not considered because external exposure is insignificant for the substances considered and the inhalation of dust is insignificant for the restoration options considered.

The exposure pathways to the public were calculated, using steady state factors, for the uptake by biota and further transfer along the food chains. The exposure pathways for the critical group are indicated in the compartment scheme (Figure 4). These are

- consumption of water
- consumption of fish
- consumption of milk and meat from cattle drinking water

The committed collective intake/dose is based on production data.

## 5.3 Doses to public

The doses calculated consist of individual and committed collective intakes/doses.

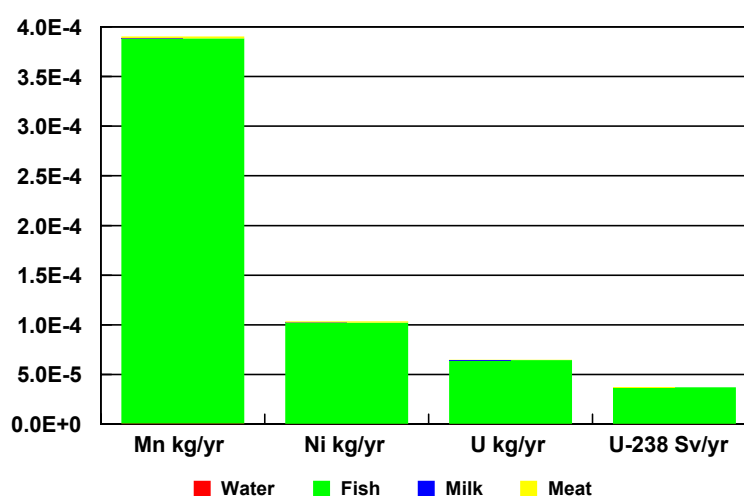
### 5.3.1 Individual doses to critical group (public): 1<sup>st</sup> year

The results of the dose calculations for the individual doses at Year 1 are shown in Table 13.

**Table 13 Individual dose (Sv/a) and intake (kg/a) at Ranstad tailing site at Year 1.**

Exposure pathway	Manganese kg/a	Nickel kg/a	Uranium kg/a	U-238 Sv/a
	Mean	Mean	Mean	Mean
Water	5.96E-07	3.50E-09	5.57E-09	3.19E-09
Fish	3.88E-04	1.02E-04	6.44E-05	3.68E-05
Milk	5.33E-09	1.28E-08	6.29E-09	3.60E-09
Meat	1.80E-06	1.25E-06	2.20E-07	1.26E-07
Total	3.90E-04	1.03E-04	6.46E-05	3.70E-05

The contribution to the total intake/dose from different pathways is shown in Figure 5.



**Figure 5 The contribution to the total dose (Sv/a) and intake (kg/a) from different pathways.**

The intake of fish from the M-lake is the dominating exposure pathway for all heavy metals as well as for uranium-238.

### 5.3.2 Collective doses to public over 100 years and 500 years

Relevant restoration options for the Ranstad tailing site have been described in Stiglund (1999). The effects of different restoration techniques are mainly given by different decontamination factors (Df-factors). The source term is divided by the Df-factor in order to reduce it in proportion to the effect of the restoration technique. Infiltrating water is reduced when capping is considered, so for this restoration technique the amount of infiltrating water have been reduced in proportion to the efficiency of the cover system. The base case, as the situation is without any restoration, is called Option A.

Table 14 shows the restoration options considered for the Ranstad tailing site.

**Table 14 Restoration options considered for the Ranstad site.**

Case	Restoration option
A	Base case
C1	Soil washing
D1	Chemical solubilisation
E1	Capping, 0.5 m moraine
E2	Capping, 1.6 m
F2	Physical immobilisation, <i>in-situ</i>
G2	Chemical immobilisation, <i>in-situ</i>

The results of the dose calculations for the collective intakes/doses at 100 years and 500 years for the different restoration options are shown in Table 15.

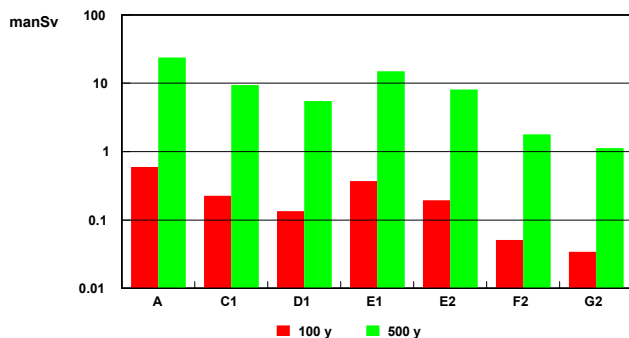
**Table 15 Collective intake, (mankg), and doses, (manSv), at the Ranstad tailing site**

Case	Year	Manganese mankg Mean	Nickel mankg Mean	Uranium mankg Mean	Uranium manSv Mean
A	100	1.2E+01	8.8E-01	1.0E+00	5.9E-01
	500	2.2E+01	5.8E+01	4.2E+01	2.4E+01
C1	100	6.3E+00	3.5E-01	4.0E-01	2.3E-01
	500	1.3E+01	2.2E+01	1.7E+01	9.4E+00
D1	100	5.1E+00	2.3E-01	2.3E-01	1.3E-01
	500	1.0E+01	1.2E+01	9.6E+00	5.5E+00
E1	100	7.9E+00	5.6E-01	6.5E-01	3.7E-01
	500	1.6E+01	3.5E+01	2.6E+01	1.5E+01
E2	100	4.4E+00	3.1E-01	3.4E-01	1.9E-01
	500	9.4E+00	1.8E+01	1.4E+01	8.1E+00
F2	100	1.3E+00	1.1E-01	8.9E-02	5.1E-02
	500	3.8E+00	4.0E+00	3.1E+00	1.8E+00
G2	100	7.3E-01	7.5E-02	6.0E-02	3.4E-02
	500	2.9E+00	2.5E+00	2.0E+00	1.1E+00

As can be seen in Table 15 the intake of heavy metals and the committed collective dose from uranium-238 are quite high. This is due to the consumption of water from the limestone aquifer. Since the time of transport for the leachate down to the limestone is rather long, some hundred years will pass before the groundwater in the limestone becomes heavily contaminated.

In Figure 6 the collective dose commitment from uranium-238 for the public is graphically depicted for the different restoration options at 100 and 500 years.





**Figure 6** The total collective dose of uranium-238 (manSv) for the different restoration options at 100 years and 500 years.

As can be seen in Figure 6 the reduction of committed dose to the public is quite small for the different restoration options except for Options F2 and G2. It seems that the physical and chemical immobilisation is the most effective among the restoration options in order to reduce the dose.

## 6 Ranking of restoration options

Decisions on clean-up in long-lasting exposure situations may well go far beyond purely radiological protection considerations. Satisfying the justification principle requires that the overall effect of the actions involved should do more good than harm, taking account of relevant radiological and non-radiological factors. Most decisions require multiple criteria to be taken into account. The field of multiple criteria analysis offers a number of approaches which take explicit account of multiple criteria in providing structure and support to the decision-making process. In case of restoration of contaminated sites there are several criteria or attributes that need to be considered when choosing an 'optimum' restoration strategy. When the performance and costs of all the protection options have been assessed, a comparison is needed to define the *optimum* protection option. When the optimum is not self evident, the comparison can be carried using a quantitative decision-aiding technique. Of the different techniques available, cost-benefit analysis and multi-attribute utility analyses have been used for ranking different remediation options. Both radiological and non-radiological issues have been addressed in the analyses.

### 6.1 Method

The attributes that have been considered in this study include:

- *Health attributes*
  - collective doses to population
  - doses to remediation workers
    - non-radiological health factors
- *Economic attributes*
  - costs of remedial actions (incl. costs of labour and monitoring)
  - costs of monitoring of remedial options
  - costs of disposal of generated waste (in broad categories)
    - loss/gain of taxes due to loss/gain of income
- *Social attributes*
  - reassurance of the public
    - discomfort, disturbance and anxiety from the remedial action
    - loss/gain of income

The major attributes are *radiation induced health effects*, *monetary costs* and *social costs* and each of these attributes are divided into sub-attributes.

A utility,  $u$ , or utility function,  $u(x)$ , will express the score or utility of a given attribute with value,  $x$ , for a given protective option. A risk neutral utility function can in general terms be defined as:

$$u(x) = 100 \cdot \left( 1 + \frac{x_{\min} - x}{x_{\max} - x_{\min}} \right)$$

where  $(x_{\min}; x_{\max})$  is the value range of the attribute considered.

The utilities,  $u$ , and weighting factors,  $w$ , (see Hedemann Jensen (1999)) will determine the best (optimised) strategy or option amongst a set of strategies or options,  $i$ , expressed by the overall score,  $U_i(x)$ , which has its maximum value at the optimum:

$$U_i(x) = \sum_{j=1}^n w_j \cdot u_{ij}(x) \quad \text{and} \quad U_{opt} = \max \langle U_i(x) \rangle$$

The monetary costs,  $X$ , of each of the remediation options together with the averted collective doses,  $\Delta S$ , for the affected population and the collective dose,  $S_{work}$ , to the workers implementing the remedial measures will determine the net benefit,  $\Delta B$ , of the measures:

$$\Delta B = \alpha \cdot \Delta S - [\alpha \cdot S_{work} + \sum X] > 0$$

which should be positive for the option to be justified. All options with a positive net benefit are therefore justified on economic grounds the optimised option being the one with the largest net benefit.

## 6.2 Evaluation of options

The following restoration options to reduce population doses have been identified:

- A. *No remediation*
- C1. *Physical Separation*
- D1. *Chemical Separation*
- E. *Containment*
  - E1. Capping 0.5 m
  - E2. Capping 1.6 m
- F2. *Physical Immobilisation*
- G2. *Chemical Immobilisation*

The economical and radiological data for remediation of the Ranstad site are shown in Table 16. The monetary costs,  $X$ , of the remediation strategies can be compared to the benefit of the collective dose reduction,  $\Delta S$ . The net benefit,  $\Delta B$ , is given as:

$$\Delta B = \alpha \cdot \Delta S - (X_{remedia} + X_{waste})$$

None of the remedial options are justified on economic grounds alone when only the central estimates of collective dose are used together with an  $\alpha$ -value of 100,000 ECU·manSv<sup>SYMBOL-1</sup>. Not even a higher value of  $\alpha$  (e.g. 200,000 ECU·manSv<sup>SYMBOL-1</sup>) and more extreme values from the calculated collective dose distribution (e.g. the 95th percentile) would make any of the options economically justified for any of the integration times for the collective doses.

**Table 16 Remediation costs and collective doses to population and workers for different restoration strategies at the Ranstad site.**

Restoration strategy	Collective dose to population [man Sv]		Collective intake of metals to population [man·kg]		Monetary costs of restoration [kECU]		Fraction of activity left on-site
	100 y	500 y	100 y	500 y	Remediation	Waste disposal	
	Manganese/Nickel						
A	0.59	23.7	12/8.8	22/58	0	0	1
C1	0.23	9.4	6.3/0.35	13/22	640,000	38,000	0.4
D1	0.13	5.5	5.1/0.23	10/12	730,000	38,000	0.2
E1	0.37	15.0	7.9/0.6	16/35	9,500	0	1
E2	0.19	8.1	4.4/0.31	9.4/18	16,000	0	1
F2	0.051	1.8	1.3/0.11	3.8/4.0	23,000	0	1
G2	0.034	1.1	0.73/0.08	2.9/2.5	32,000	0	1

The individual doses from food intake would in average be of the order of 10 - 100  $\mu\text{Sv}\cdot\text{a}^{\text{SYMBOL-1}}$  at the time of decision to introduce remediation (Year 1). IAEA has proposed clean-up criteria in terms of individual dose. For an individual dose range of 10 - 100  $\mu\text{Sv}\cdot\text{a}^{\text{SYMBOL-1}}$  clean-up is sometimes needed if a constraint for controlled practices is applied. Without the application of a constraint IAEA suggests that for individual doses of 10 - 100  $\mu\text{Sv}\cdot\text{a}^{\text{SYMBOL-1}}$  cleanup would rarely be needed. Based on these recommendations it can be concluded that remediation would probably not be justified for the Ranstad site.

### 6.2.1 Utilities

Utility functions for the attributes *monetary costs* and *radiation doses* have been calculated from the data in Table 16 on monetary cost components and residual collective doses after remediation. Linear (risk neutral) utility functions have been used.

#### Utility functions for monetary costs

Utility functions ( $u(x)$ ) have been determined for remediation costs (including labour costs), waste disposal costs (including transport costs) and monitoring costs:

$$u_{\text{remedia}}(x) = 100 \cdot \left( 1 - \frac{x}{730,000} \right) \quad \text{for } 0 \leq x \leq 730,000 \text{ kECU}$$

$$u_{\text{waste}}(x) = 100 \cdot \left( 1 - \frac{x}{38,000} \right) \quad \text{for } 0 \leq x \leq 38,000 \text{ kECU}$$

#### Utility functions for health factors

The following utility functions for the radiological health components have been determined for the exposed population and workers implementing the remedial actions. Both radiological and non-radiological health factors are considered for the Ranstad site as nickel and manganese would expose the population through contaminated foodstuffs.

$$u_{dose, pop, 100}(x) = 100 \cdot \left( 1 + \frac{0.034 - x}{0.59 - 0.034} \right) \text{ for } 0.034 \leq x \leq 0.59 \text{ man Sv}$$

$$u_{dose, pop, 500}(x) = 100 \cdot \left( 1 + \frac{1.1 - x}{23.7 - 1.1} \right) \text{ for } 1.1 \leq x \leq 23.7 \text{ man Sv}$$

$$u_{non-rad, 100}(x) = 100 \cdot \left( 1 + \frac{0.21 - x}{20.8 - 0.81} \right) \text{ for } 0.81 \leq x \leq 20.8 \text{ man kg nickel + manganese}$$

$$u_{non-rad, 500}(x) = 100 \cdot \left( 1 + \frac{5.4 - x}{80 - 5.4} \right) \text{ for } 5.4 \leq x \leq 80 \text{ man kg nickel + manganese}$$

### Utility functions for social factors

The utility function  $u_{reas}$  for reassurance would be linked to both the residual dose and the fraction of activity remaining on the site after the remedial measure has been implemented. However, the residual dose and remaining activity are not necessarily correlated. A remedial measure that has left all the activity on site in a contained form (capping, surface barriers etc.) might give a substantial dose reduction and thus a low value of the residual doses. Detailed information on how social factors like reassurance are linked with individual doses and activity concentration on site is not available. Therefore, utility functions for 100 years and 500 years integration time have been proposed which gives a low value only when both sub-utilities have low values:

$$u_{reas, 100}(x, y) = 100 \cdot \left( \frac{1}{2} \cdot \left( 1 + \frac{0.034 - x}{0.59 - 0.034} \right)_{dose} + \frac{1}{2} \cdot \left( 1 + \frac{0.2 - y}{1.0 - 0.2} \right)_{activity} \right)$$

for  $0.034 \leq x \leq 0.59$  man Sv and  $0.2 \leq y \leq 1$

$$u_{reas, 500}(x, y) = 100 \cdot \left( \frac{1}{2} \cdot \left( 1 + \frac{1.1 - x}{23.7 - 1.1} \right)_{dose} + \frac{1}{2} \cdot \left( 1 + \frac{0.2 - y}{1.0 - 0.2} \right)_{activity} \right)$$

for  $1.1 \leq x \leq 23.7$  man Sv and  $0.2 \leq y \leq 1$

where  $y$  is the fraction of activity remaining on site after the remedial measures has been implemented. The value of the utility function  $u_{reas}$  is 100 for a residual dose of 0.034 (1.1) man Sv and a remaining fraction of the initial activity of 0.2 (best strategy) and 0 for a residual dose of 0.59 (23.7) man Sv and a remaining activity fraction of 1.0 (worst strategy).

The utility function  $u_{distur}$  for disturbance has been related to the volume of waste (expressed by the waste disposal costs) to be transported to the waste disposal site:

$$u_{distur}(x) = 100 \cdot \left( 1 - \frac{x}{38,000} \right) \text{ for } 0 \leq x \leq 38,000 \text{ kECU}$$

### 6.2.2 Weighting factors

Weighting factors are scaling factors that reflect the relative importance of each of the attributes. The weighting factors assigned to the different attributes at the same hierarchy level can be determined by either the ratio of value ranges,  $R$ , of the attributes or by assigning values to the ratio of the weighting factors at that level. Both methods have been used here.

### Weighting factors for major attributes

The major weighting factors considered in this study include those for monetary costs, health and social factors. The sum of these weighting factors should respect the following conditions:

$$w_{health} + w_{economic} + w_{social} = 1$$

The assessment of the weighting factors is discussed in Hedemann Jensen (1999) where conversion/scaling constants between weighting factors has been expressed as:

$$C_1 = \frac{w_{economic}}{w_{health}} \cong \frac{w_{economic}}{w_{dose, pop}} = \frac{R_{economic}}{\alpha \cdot R_{dose, pop}}$$

$$C_2 = \frac{w_{social}}{w_{health}} \approx \frac{r_{psy}}{r_{rad}}$$

The value of  $C_1$  can be determined for a 100 and 500 years integration time for the collective dose from the values given in Table 16?. The value of  $C_2$  is more difficult to assess but a value of 0.2 - 0.3 has been argued for in Hedemann Jensen (1999). From these values of  $C_1$  and  $C_2$  the weighting factors for health, economic and social factors have been calculated as shown in Table 17.

### Weighting factors for health sub-attributes

The weighting factors for health sub-attributes include those of radiation induced stochastic health effects to the affected population and workers and non-radiation induced stochastic health effects to the affected population. The sum of these weighting factors should respect the following conditions:

$$w_{dose, pop} + w_{non-rad, pop} = 1$$

The conversion/scaling constant,  $C$ , for the health sub-attributes can, according to Hedemann Jensen (1999), be expressed as:

$$w_{dose, pop} = C \cdot R_{dose, pop} \cdot l \cdot r_{rad} \cong C \cdot R_{dose, pop}$$

$$w_{non-rad, pop} = C \cdot R_{non-rad, pop} \cdot l \cdot r_{rad}$$

The conversion/scaling constant,  $C$ , can be determined from the dose ranges,  $R$ , given in Table 16 (see Hedemann Jensen (1999)).

$$C \cong \frac{1}{R_{dose, pop} + R_{dose, work}}$$

From the calculated values of  $C_{100}$  and  $C_{500}$  (see Hedemann Jensen (1999)) the weighting factors for collective population and worker doses have been calculated as shown in Table 17.

### Weighting factors for economic sub-attributes

The weighting factors for economic sub-attributes include those for cost of remediation and costs of waste disposal. The sum of these weighting factors should respect the following conditions:

$$w_{remedia} + w_{waste} = 1$$

The conversion/scaling constant,  $C$ , for the economical sub-attributes can, according to Hedemann Jensen (1999), be expressed as:

$$w_{remedia} = C \cdot R_{remedia} \quad \text{and} \quad w_{waste} = C \cdot R_{waste}$$

The conversion/scaling constant,  $C$ , can be determined from the cost ranges,  $R$ , given in Table 16 and the weighting factors for remediation and waste disposal costs have been calculated as shown in Table 17.

### Weighting factors for social sub-attributes

The weighting factors include those for reassurance and disturbance. The sum of these weighting factors should respect the following conditions:

$$w_{distur} + w_{reas} = 1$$

The conversion/scaling constants for the social sub-attributes can, according to Hedemann Jensen (1999), be expressed as:

$$C_1 = \frac{w_{reas}}{w_{distur}}$$

In Hedemann Jensen (1999) it is argued that  $w_{reas} > w_{distur}$  and that  $C_1 \approx 5 - 7$ . From these values the weighting factors for reassurance and disturbance have been calculated as shown in Table 17.

**Table 17 Weighting factors for attributes and sub-attributes applied in the optimisation of remediation of the Ranstad site. The values in the left of the double columns are for an integration time of 100 years and in the right column for an integration time of 500 years.**

Health factors			Economical factors		Social factors	
$7.2 \cdot 10^{-5}$	$2.9 \cdot 10^{-3}$		0.999	0.996	$1.8 \cdot 10^{-5}$	$7.3 \cdot 10^{-4}$
Dose populaation	1	1	Remediation cost	0.95	Reassurance	0.86
Dose workers	-	-	Waste disposal cost	0.05	Disturbance	0.14

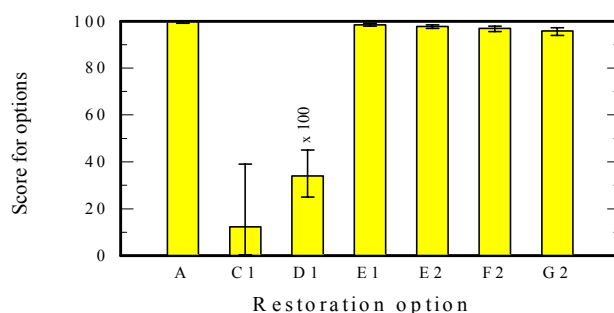
It should be emphasised that value setting of weighting factors is the crucial issue of any optimisation because subjective judgements inevitably will enter the process.

### 6.3 Results

The overall scores,  $U_i$ , of the remediation options  $i$  has been determined from the weighted sum of utilities for each of the attributes considered:

$$\begin{aligned}
 U_i &= \sum_{j=1}^3 w_j \cdot u_{ij} \\
 &= w_{health} \cdot (w_{dose, pop} \cdot u_{dose, pop} + w_{non-rad} \cdot u_{non-rad}) \\
 &\quad + w_{economic} \cdot (w_{waste} \cdot u_{waste} + w_{remedia} \cdot u_{remedia}) \\
 &\quad + w_{social} \cdot (w_{distur} \cdot u_{distur} + w_{reas} \cdot u_{reas})
 \end{aligned}$$

The weighting factors above have all been sampled in a triangular distribution between 0.67 - 1.5 times the most probable value given in Table 17. Similarly, the values of all the utilities,  $u(x)$ , are determined from the utility functions in which the values of  $x$  are sampled in a triangular distribution between 0.67 - 1.5 times the central values of  $x$  given in Table 16. Negative correlation between collective doses and remediation costs has been applied with a correlation coefficient of  $-0.8$ . The evaluation of the different strategies has been made with the forecasting and risk analysis program CRYSTAL BALL. Latin Hypercube Sampling technique was used and the number of trials were 10,000. The results for the scores,  $U_i$ , for the options A1 - G2 are shown in Figure 7.. The error bars represent the 5% and 95% percentiles of the distributions of  $U_i$ .



**Figure 7 Overall evaluation of scores for different remediation strategies for the Ranstad site for an integration time of 100 and 500 years for the collective dose.**

As can be seen from Figure 7, Option A has the highest score. Options E1, E2, F2 and G2 have all a more or less equal score, not significantly lower than that of Option A. Options C1 and D1 both have a low score due to high remediation and waste disposal costs. The 'no remediation' option, Option A, can thus be considered as the optimum solution for the Ranstad site and also the cheapest. There is no difference between the scores for the two different integration times due to the low weight of the health attributes.

The ranking of the different remedial measures using multi-attribute utility analyses allows the inclusion of factors that are not easy to quantify in monetary terms as is required in cost-benefit analysis. The weighting factors assigned to the different attributes have been determined by use of scaling factors in terms of weighting factor ratios, and their values were sampled around a most probable value. Notwithstanding this advantage of the multi-attribute method there are difficulties with the determination of weighting factors for the different attributes. Without any terms of reference for the weighting between attributes, value settings by a decision-maker could lead to 'optimised' results that might be useless because of a subjective bias of the decision-maker in the selection of weighting factors. Therefore, the outcome of any multi-attribute analysis, including the present study, should be judged very carefully in the light of the values assigned to the weighting factors before any firm conclusions could be drawn.



## 7 Conclusion

The objectives of this technical deliverable has been to use Ranstad mill tailing site as an example, in the decision-making procedure for remediation, developed by RESTRAT. The procedure involved characterisation of the site with available data, identification of contamination source, identification of critical group and exposure pathways through which man can be exposed to these contaminants and dose assessment for different remediation alternatives. This information was combined with the calculation of economic and social costs in a multi-attribute utility analysis to rank each restoration technique.

This exercise was performed on a hypothetical case, as it was assumed that no remediation (covering of the mill tailing) had previously been carried out on the site. The site has been remedied according to Option E2, which is capped with layer of different material.

The result show that the “no remediation option” was the most favourable remediation alternative, but the two capping options, physical and chemical immobilisation was more or less equally favourable almost in the same range as no action. The ranking of the different remedial measures using multi-attribute utility analysis allows the inclusion of factors that are not easy to quantify in monetary terms as is required in cost-benefit analysis which give an essential support in the decision procedure. However, the values of the weighting factors used in the present study should be evaluated carefully before any final conclusions should be made.

The present study identified several options which could be potentially useful, and that capping, the restoration option actually used, was among these options.

## **8 Acknowledgement**

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