



GEOCHEMICAL TEST WORK IN ENVIRONMENTAL IMPACT ASSESSMENTS FOR MINING PROJECTS IN GREENLAND

– Recommendations by DCE and GINR

Technical Report from DCE – Danish Centre for Environment and Energy No. 132 2018



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Abstract:	This report by Danish Centre for Environment and Energy (DCE) and Greenland Institute for Natural Resources (GINR) provides background information and a set of recommendations for geochemical test work required for Environmental Impact Assessments (EIAs) for mining projects in Greenland. The report include specific recommendations for identification and characterization of rock and waste units, description of mine components, collection of samples, selection of test methods, interpretation of test results, predictions and reporting. Further, the report includes recommendations for a work flow that will enable an improved time-efficient dialogue between the companies, the authorities and its advisors regarding the requirements for geochemical test work, interpretation of the results and finally inclusion of the predictions in the EIA.
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Contents

Preface	5
List of Abbreviations	6
Summary	7
Sammenfatning	8
Imaqarniliaq	9
Scope	10
1. Work flow	11
2. Identification and characterization of rock and waste units	12
3. Mine components and site-specific conditions	13
4. Sampling	14
4.1 Sample types	14
4.2 Sample description	14
4.3 Sample number	15
4.4 Sample method	16
4.5 Sample dimensions	17
4.6 Sample mass	17
4.7 Sample preparation and storage	18
5. Overview of geochemical tests	20
6. Static tests	22
6.1 Elemental analyses	22
6.2 Mineralogy	24
6.3 Acid-base accounting	26
6.4 Net acid generation	28
6.5 Paste pH _{1:2} and EC _{1:2}	29
6.6 Water leaching (Shake flask)	29
6.7 Sequential extraction	31
6.8 Radon release	31
6.9 Toxicity	33
7. Kinetic tests	35
7.1 Humidity cell	35
7.2 Sub-aerial column	37
7.3 Sub-aqueous column	37
7.4 Intermittent bottle roll	38
7.5 Pilot scale tests in the field	39

8. Interpretation of test results and model predictions	40
9. References and additional literature	44

Preface

According to the Greenland Parliament Act no. 7 of 2009 on mineral resources and mineral resource activities (the Mineral Resources Act) with later amendments, mining companies operating in Greenland must prepare an Environmental Impact Assessment (EIA) for public consultation and government approval in connection with the development of a mining project and prior to obtaining an exploitation license.

An important part of EIAs for mining projects concerns understanding and predicting mobilization and leaching of pollutants from mine waste products to the environment. For this purpose, geochemical test work (incl. other waste characterization tests such as radon release and toxicity tests) plays a central role. Today, a number of geochemical test methods exist to assess the geochemical behavior of ore, waste rock and tailings from the mining industry and to predict leaching of pollutants from these sources.

Geochemical studies are covered broadly in the EIA guidelines for mining projects in Greenland (Mineral Resources Authority, 2015). However, experiences from recent draft EIA reports for mining projects in Greenland have shown that there is a need for more specific recommendations for the geochemical test work. Geochemical studies typically take several months to complete and if the required studies are not carried out in time, it can delay a mining project significantly.

This report provides background information and a set of specific recommendations for geochemical test work (incl. radon release and toxicity tests) required for EIAs for mining projects in Greenland. The recommendations are based on existing guidelines from Canada, US, Australia and international organizations (and aim to be at the same level as these) and include DCE's and GINR's experience from previous projects in Greenland.

The purpose of the recommendations is both to enable the mining companies to understand and fulfill the requirements for geochemical test work at an early stage of the mining project and to ensure that the test work is in line with requirements in other mining countries such as Canada, US and Australia with high environmental standards.

List of Abbreviations

ABA: Acid Base Accounting

AP: Acid Potential

ARD: Acid Rock Drainage

Bq: Becquerel

EC: Electrical Conductivity

EDS: Energy Dispersive X—Ray Spectroscopy

Eh: Redox potential

EIA: Environmental Impact Assessment

HC: Humidity Cell

IAEA: International Atomic Energy Agency

IBR: Intermittent Bottle Roll

ICP-MS: Inductively Coupled Plasma Mass Spectrometry L/S: Liquid/Solid

ML: Metal Leaching

NAG: Net Acid Generating

NOR: Naturally Occurring Radionuclides

NORM: Naturally Occurring Radioactive Material

NP: Neutralization Potential

NPR: Neutralization Potential Ratio

PAG: Potentially Acid Generating

PIXE: Proton Induced X-Ray Emission

QA: Quality Assurance

QC: Quality Control

SAQC: Sub-Aqueous Column

SAEC: Sub-Aerial Column

SEM: Scanning Electron Microscopy

SIMS: Secondary Ion Mass Spectrometry

XRD: X-Ray Diffraction

XRF: X-Ray Fluorescence

Summary

An important part of Environmental Impact Assessments (EIAs) for mining projects in Greenland and elsewhere concerns prediction of leaching of potential pollutants from mine waste to the environment. For this purpose, geochemical test work plays a central role. Currently there is a need for a set of specific recommendations for geochemical test work for mining projects in Greenland. Such recommendations will enable mining companies operating in Greenland to understand and fulfill the requirements for geochemical test work at an early stage of the mining project and contribute to adequate information during the EIA process.

This report by Danish Centre for Environment and Energy (DCE) and Greenland Institute for Natural Resources (GINR) provides background information and a set of recommendations for geochemical test work (incl. radon release and toxicity tests) required for EIAs for mining projects in Greenland. The report include specific recommendations for identification and characterization of rock and waste units, description of mine components, collection of samples, selection of test methods, interpretation of test results, predictions and reporting. Also, the report includes recommendations for a work flow that will enable an improved time-efficient dialogue between the companies, the authorities and its advisors regarding the requirements for geochemical test work, interpretation of the results and finally inclusion of the predictions in the EIA.

The recommendations are based on existing guidelines from Canada, US, Australia and international organizations (and aim to be at the same level as these) and are built on DCE's and GINR's experience from previous mining projects in Greenland.

Sammenfatning

En vigtig del af miljøkonsekvensvurderinger (såkaldte Vurderinger af Virkninger på Miljøet (VVM) redegørelser) for mineprojekter omhandler forudsigelser af udvaskning af potentielt miljøfarlige stoffer fra mineaffald til miljøet. Til det formål spiller geokemiske tests en central rolle. Der er pt. behov for et sæt specifikke anbefalinger i forhold til det geokemiske test arbejde i forbindelse med udarbejdelse af VVM redegørelser for mineprojekter i Grønland. Sådanne anbefalinger vil give mulighed for, at mineselskaber, der opererer i Grønland, på et tidligt tidspunkt i projekterne kan forstå og opfylde kravene til det geokemiske test arbejde.

Denne rapport udarbejdet af Nationalt Center for Miljø og Energi (DCE) og Grønlands Naturinstitut (GN) giver baggrundsinformation og et sæt specifikke anbefalinger for geokemisk test arbejde (inkl. radon frigivelsestests og økotoxikologiske tests), der bør kræves i forbindelse med VVM redegørelser for mineprojekter i Grønland. Rapporten indeholder specifikke anbefalinger i forhold til identifikation og karakteristik af affaldsenheder, beskrivelse af mine-komponenter, prøveindsamling, udvælgelse af test metoder, fortolkning af test resultater, forudsigelser og rapportering. Endelig giver rapporten også anbefalinger til en arbejdsgang, der skal sikre en hensigtsmæssig og rettidig dialog mellem mineselskaberne, myndighederne og rådgiverne i forhold til det geokemiske test arbejde, fortolkning af test resultaterne og endelig indarbejdning af forudsigelserne i VVM redegørelsen.

Anbefalingerne bygger på eksisterende retningslinjer fra Canada, USA, Australien og internationale organisationer (og tilstræber at være på niveau med disse) samt bygger på DCE's og GN's erfaringer fra tidligere mineprojekter i Grønland.

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Scope

This set of recommendations aim to provide mining companies and their consultants that operate in Greenland with an overview and checklist of geochemical test work and other waste characterization tests required in connection with Environmental Impact Assessments (EIAs) of mining projects. For the exploration phase of the mining projects, there is currently no requirements for geochemical test work. However, storing samples obtained during the exploration phase of the projects will be beneficial if the company decides to continue with development of the project and make an EIA as part of an exploitation application.

The recommendations aim to provide a good starting point for setting up an adequate geochemical test program for EIAs for new mining project in Greenland. However, the list of tests may not be complete and not all the tests described will be relevant to all projects. It is important to note that the final geochemical test program should always be tailored to the specific mining project since all mining projects are unique due to factors such as geology, climate, hydrology, scale of the project and mining-, processing- and waste deposition method.

1. Work flow

Since geochemical test work is an important part of EIAs for mining projects and can take up to years to complete, it is important to develop and get the geochemical test program approved by the Greenland Authorities and initiate the test work at an early stage of the EIA process to avoid any delay in the project.

The preparation and reporting of the geochemical test work is considered a three-step process:

- 1) At first, a proposed geochemical test program should be developed and sent to the Greenland Authorities approval or comments. This should include:
 - a. An overall description of rock and waste units and mine components for the projects (Chapter 2 and 3)
 - b. A detailed description of the proposed samples for geochemical testing including a map showing location and depths of sampling (Chapter 4)
 - c. A detailed description of the proposed static tests for the projects (Chapter 6)
- 2) Next, a preliminary assessment report should be made based on the results of the static tests and sent to the Greenland Authorities for approval or comments. This should include:
 - a. All original data and laboratory reports (incl. QC data)
 - b. An assessment of the data with regard to geochemical properties and implications for leaching
 - c. A detailed description of proposed further kinetic tests (if relevant) and perhaps additional static tests on selected samples (Chapter 6 and 7)
- 3) Last, a final assessment report should be made on the results from all tests and sent to the Greenland Authorities for approval or comments. Approval means that the Greenland Authorities agree that the report is correct and fulfils the requirements for the EIA. The final assessment report should include:
 - a. All original data and laboratory reports (incl. QC)
 - b. A detailed description of rock and waste units and mine components for the projects (Chapter 2 and 3)
 - c. A detailed description of the samples used for geochemical testing (Chapter 4)
 - d. An assessment of all data from both the static and kinetic tests and predictions of the resulting drainage chemistry and effects from all mine components throughout the life of the mine and after closure (Chapter 8).

In case of unexpected results reported in Pt. 2 and 3 above, more geochemical test work may eventually be required than previously approved in the test program.

After the Greenland Authorities has approved the final assessment report, results should be included in the EIA and the assessment report should be available to the public during the hearing phase.

The following chapters describe recommendations for geochemical test work including characterization, test methods and interpretation.

2. Identification and characterization of rock and waste units

All rock and waste units exposed or disturbed by mining, milling, concentrating or construction should be identified in the project. These units can be grouped into waste rock, ore and tailings, respectively, and should be characterized in terms of:

- Location, depth and spatial extent (shown on map)
- Geology/lithology (different main lithological units should be treated separately)
- Total volume/tonnage
- Size fractionation.

The term 'waste rock' used here includes all rocks exposed or disturbed in the project, also so-called 'overburden', which is sometimes referred to separately in the literature.

All these units should be subject to sampling as described in the following.

3. Mine components and site-specific conditions

Specific rock and waste units should be separated into mine components such as waste rock dumps, tailings facilities, stock piles of ore and low-grade ore, open pits etc. depending on the type and location of these.

For each mine component, at least the following site-specific conditions should be given:

- Location (shown on map)
- Dimensions (incl. ground surface area and height)
- Air temperature (annual/monthly averages)
- Degree of aeration (under-water or aerial, specific redox conditions)
- Hydrogeology (permafrost level, groundwater flows etc.)
- Drainage volume and frequency (based on precipitation data and surface water flow)
- Drainage chemistry (based on baseline water samples).

It may be adequate to subdivide some of the units e.g. waste rock dumps into different waste rock dumps, if a waste rock unit is planned for deposition at more than one location.

Data on climate- and hydrology at the site is also part of the required environmental baseline studies of the EIA (Mineral Resources Authority, 2015). Such data can often be obtained via ASIAQ (Greenland Survey) or the Danish Meteorological Institute (DMI).

4. Sampling

Selection and preparation of samples is a critical step in any geochemical test program and requires particularly careful consideration. The objective of the sampling is to enable analyses or test work that will describe the statistical distribution in the targeted properties of the materials (see MEND, 1994 and MEND, 2009 for a more detailed description).

4.1 Sample types

Sample types should include all the different rock or waste units (i.e. waste rocks, ore and tailings) in the project as identified in Chapter 2. For waste rock, samples should include all the main lithological units.

If mining has previously occurred at the site, old waste rock, ore residues or tailings left at the site should be sampled such it can provide valuable information on the leaching of contaminants from these materials on site.

In addition to samples from the rock and waste units, baseline (i.e. pre-mining) samples of water should be collected from all water bodies potentially affected by drainage water from the mine components identified in Chapter 3. Collection and subsequent analyses of these baseline water samples are needed to make accurate predictions of the resulting chemistry in water affected by drainage water from the mine components.

Also, in case mining has previously occurred at the site, baseline water samples collected adjacent to historic mine waste sources with near-similar characteristics as the waste rock/ore/tailings samples from the mining project in question will be valuable for comparison with predicted aquatic chemistry based on the geochemical test work and should be included in the sampling program.

4.2 Sample description

Each sample should be assigned a unique sample name or number to be able to identify the sample in the field, in the laboratory and during data analyses.

Sample sites should be plotted and shown on a geographical map. If drill cores are used, the location of the samples should also be shown on geological cross-sectional map.

Further, a description should be provided with each sample covering the following:

- Sampling date
- Sampler's name
- Sampling location and depth
- Sample type (drill core, surface sample etc.)
- Sample dimension (i.e. the area, volume or length over which the sample is collected)
- Sample mass
- Geological classification
- Type of waste material (Chapter 2) and mine component (Chapter 3)

- Visual characteristics (e.g. Munsell colour, visible mineralogy and apparent grain size)
- Photo of the sample.

The information above can become critical for correct interpretation of the test results later on.

Photo 1. Drill cores at the former lead-zinc mine in Maarmorilik, West Greenland. Photo: Lis Bach



4.3 Sample number

A sufficient number of samples should be collected to be able to determine the statistical distribution (i.e. the variability¹ and central tendency²) of relevant geochemical properties in the rock and waste units.

Variation in geochemical properties can result from differences in lithology, mineralization and alteration within the rock and waste units (i.e. the ore, waste rock and tailings).

The number of samples required for the geochemical work is specific to each project and will depend on factors such as:

- Type of rock and waste units
- Tonnage of material
- Variation of critical geochemical properties in the material (can first be assessed once a significant number of samples have been analysed)
- Available information from previous studies at the site.

¹ Variability here refers to the range, median and 10% and 90% percentiles

² Central tendency here refers to the arithmetic mean and standard deviation (if the data is normal or log normal distributed). If not, other appropriate statistics should be used.

For initial sampling and testing, and in case no prior information is available, the following table from MEND (2009) can be used as a starting point for sample selection.

Table 1. Suggested initial sampling frequency per rock and waste unit based on tonnage in case no prior information is available (from MEND, 2009).

Tonnage of unit (metric tonnes)	Minimum number of samples
<10,000	3
<100,000	8
<1,000,000	26
<10,000,000	80

The suggested minimum sample numbers follow the equation (MEND, 1994):

$$N = 0.026 * M^{0.5}$$

Where N is the minimum sample number and M is the tonnage (in tons).

For baseline water samples, enough samples should be collected to account for both spatial and temporal variations in aquatic chemistry at the sites.

4.4 Sample method

Waste rock, ore and tailings samples

Prior to the mine development, sampling for waste rock and ore will usually consist of drill cores that are subsequently crushed down for tests and analyses. When using drill core samples, it should be taken into account that easily soluble minerals (such as e.g. villaumite (NaF)) may be underestimated due to dissolution of these minerals on the surface of the drill cores in the drilling fluid.

If, however, some waste rock and ore have been extracted by blasting during the exploration phase, this can provide valuable information on the grain size distribution due to blasting in the mining process as well as information on the geochemical characteristics of the fine size fractions. In that case, a size distribution analysis of the material should be made and fresh samples of the fine size fraction (< 2 mm particle size) should be taken and included in the subsequent tests and analyses.

Tailings samples should be taken from pilot scale testing of the processing circuit. It is important that the ore sample that goes into the pilot scale testing is representative to the ore material that is planned to be mined and that the pilot scale testing uses the same processing technique and chemicals that is planned in the project. If the technique or processing chemicals change, new tailings samples should be taken.

Any old waste rock, ore residues and tailings at the site from previous mining activity (if it exists) should be sampled and treated as it is without further crushing. This is to allow a subsequent comparison between the chemical composition of old and fresh mineral surfaces.

Water samples

Baseline water samples should be taken as both unfiltered and filtered samples (filtered to $<0.45\ \mu\text{m}$ in size) to allow for analyses of both the total and dissolved element concentrations in the water, respectively. Since the element concentrations are often very low, special care should be taken not to contaminate the samples during sampling. Samples should be filtered in situ in the field or shortly after arrival in the camp (within a few hours) as water samples are prone to chemical changes when stored. Subsamples of the water should be measured for pH and electrical conductivity (EC).

4.5 Sample dimensions

Since mine waste materials are not homogeneous (especially so for waste rock) and since the mining process in a typical mining project takes many years and typically involves mining of different lithological units, it is important to consider sample dimensions when sampling. It is critical that the sampling of waste rock, ore and tailings and the subsequent runoff chemistry predictions reflect the variation in drainage water chemistry that can be encountered at the site at any given time.

Sample dimensions (i.e. the area, volume or depth from which a sample is taken, or from which sub-samples are composed) should consequently be carefully selected based on factors contributing to variations in drainage water. Such factors include:

- Proposed methods and rates of extraction, exposure and deposition of the waste materials
- Total volume of the waste materials
- Variations in geochemical properties of the waste materials.

Samples should be spatially well-distributed in the material proposed for mining (geographically and with depth in the deposit).

For drill cores, the entire core can potentially be used but separate lithological rock units should always be separated into separate samples. It may also be adequate to split the lithological rock units into additional sub-samples to assess the variability of geochemical properties of the rock unit e.g. if the rock unit has a high variability of geochemical properties or if the rock unit is several meters thick. Depending on the mining method etc., an adequate sample dimension for a drill core sample may also be the bench height for a proposed open pit or the adit height for proposed underground workings (split into sub-samples if more than one lithological rock unit is present).

Compositing of different drill core samples (even from the same lithological rock units) or widely spaced surface rock samples should be avoided as it may mask significant variability in geochemical properties, which may lead to misclassification of potentially problematic rock sub-units.

4.6 Sample mass

The minimum required sample mass will be dictated by:

- The minimum sample mass needed to perform the geochemical analyses of concern.

- Whether the entire sample is treated as a whole and analysed (e.g. drill cores and tailings) or whether only a certain size fraction of the sample (e.g. the <2 mm size fraction, separated by sieving) is analysed (e.g. for blasted waste rock).

The following typical minimum sample masses are for material used in the geochemical tests.

For the static tests, typically a minimum of 500 g of material is needed to perform a comprehensive list of tests, with 1 kg being preferred.

For laboratory-based kinetic tests, typically a minimum of 2 kg of material is needed, with 4 kg being preferred, in addition to a minimum of 500 g for the pre-kinetic static tests.

For field-based kinetic tests (i.e. pilot scale tests), many kilograms to tonnes of material may be needed depending on the test design.

For baseline water samples, typically 100 ml samples are enough to perform the required analyses. However, the exact volume needed for the analyses should be agreed with the laboratory performing the analyses because more or less water may be needed depending on the specific analyses and procedures.

Enough material should be collected to be able to repeat the tests if appropriate.

If in doubt about the sample masses required for the geochemical test program, please contact the geochemical test laboratory once the specific geochemical test program for the project has been approved.

4.7 Sample preparation and storage

Waste rock, ore and tailings samples

Samples of waste rock and ore should be air dried, freeze dried or oven dried at low temperature after collection. Drying at temperatures no higher than 40°C will ensure that most minerals are not altered (at higher temperatures than 40°C, mercury may also evaporate from the samples). Samples should be kept cool and dry prior to and after drying.

Care should be taken to minimize changes in the geochemical conditions of the rock samples when practically possible in those cases where changes may obscure or destroy the targeted properties and processes of the subsequent analyses and test work. For example, if sulphide minerals are present in the samples, oxidation of these may occur during storage. This can be minimized by storing the samples in dry conditions or by freezing the samples.

Depending on the requirements of the specific analyses and tests in the geochemical test program, a subsample of the waste rock and ore samples should be crushed and grinded down to a certain particle size. The procedure for crushing and grinding and the resulting particle size distribution of the samples should be specified and reported.

Tailings sludge samples should be measured for pH, electric conductivity (EC), oxygen and redox potential (Eh) in the slurry as it is. For most tests, tailings samples should be air dried or freeze dried and the moisture content

and particle size distribution should be measured as part of the sample preparation. Prior to and after drying, samples should be kept cool and dry. For the leach tests, in case the tailings samples are anoxic, a subsample needs to be preserved in anoxic conditions and tested as it is (without drying) since a change in redox conditions will affect the solubility of minerals in the samples. For the toxicity test, it is preferred to use a subsample of the tailings sludge sample as it is (not dried) in order to minimize alteration of the sample and make the test as realistic as possible.

The particle size distribution of waste rock-, ore- and tailings samples used for the subsequent geochemical tests should be determined with enough detail to enable a reliable calculation of the total surface area per mass of the sample (e.g. in m^2/g) (see MEND, 2009, Chapter 16.3 and 16.4 for a detailed description). As a supplement to the size fraction analyses, the surface area of samples can also be directly measured using the so-called BET (Brunauer-Emmett-Teller) technique (as described in Strömberg and Banwart, 1999). For the leaching tests, this will enable determination of the leaching rates of elements expressed per exposed surface area of the material. This can subsequently assist when upscaling leach test results of e.g. waste rock samples (which is crushed to a fine size fraction) to real waste rock in the field, taking into account the material's actual particle size and exposed surface area.

Water samples

Water samples should typically be preserved with a clean high-quality (Suprapure or Ultrapure) nitric acid (typically 1-2 ml HNO_3 /l sample) to keep the metals dissolved. It is generally preferred that the acid is added in the laboratory after the sampling by the laboratory performing the analyses in order to minimize the risk of contamination and due to difficulties associated with transporting and handling concentrated acid in the field.

'Blank' samples should also be made by the laboratory performing the analyses using MilliQ water and the same acid as for the samples in order to be able to determine the detection limit and subtracting a 'blank' value from the sample results.

Due to limited storage stability, elemental analyses of water samples should be done as soon as possible after collection and not later than 2 years after collection (Grasshoff et al., 1999).

5. Overview of geochemical tests

An overview of the numerous geochemical tests, divided into static - and kinetic test types, is shown in Table 2 and described in detail in the following chapters. Table 2 also shows for which samples and when the different tests are typically applied in mining projects in Greenland. This is to provide a guidance of the expectations. However, each project has its own characteristics and the geochemical test program should always be tailored to the specific mining project.

Table 2. Overview of important static and kinetic tests for geochemical test work and their typical application in mining projects in Greenland. The numbers refer to chapters in this report in which they are described in more detail.

Name of test	Description	Typical application for mining project in Greenland
Static tests		
Elemental analyses (6.1)	Methods to determine element concentrations and speciation	Typically performed on all samples of water, waste rock, ore and tailings.
Mineralogy (6.2)	Methods to determine mineral abundance and concentrations	Typically performed on at least a selection of representative samples of waste rock, ore and tailings
Acid-base accounting (6.3)	Screening method to assess the net potential of samples to generate acid/base	Typically performed on all samples of waste rock, ore and tailings and is always required if the sample sulphide-sulphur content is >0.3%
Net acid generation (6.4)	Same as above but using hydrogen peroxide as an oxidizing agent	Typically performed on all samples of waste rock, ore and tailings if the sample sulphide-sulphur content is >0.3%
Paste pH and EC (6.5)	Screening method to assess the inherent acidity and salinity	Typically performed on all samples of waste rock, ore and tailings
Water leaching (Shake flask) (6.6)	Screening method to assess short-term leachability of elements in samples into water	Typically performed on all samples of waste rock, ore and tailings
Sequential extraction (6.7)	Method to assess leachability of elements in samples in different redox- and acidity conditions	Typically performed on a selection of representative samples of waste rock, ore and tailings
Radon release (6.8)	Method to determine radon release from samples	Only relevant for some projects. Typically performed on a selection of representative samples if samples are classified as NORM (see 6.8)
Toxicity (6.9)	Method to determine toxicity of leaching solutions typically using algae, crustaceans and fish as test organisms	Typically performed on tailings and on waste rock/ore leachate
Kinetic tests		
Humidity cell (7.1)	Method to determine primary minerals weathering rates and maximum leaching rates from material deposited on land on a long-term basis	Typically performed on a selection of waste rock and ore samples to enable leaching predictions from waste rock dumps, ore stock piles and mine walls

Sub-aerial column (7.2)	Method to determine leaching rates from material deposited on land on a long term basis in more realistic site-specific conditions than the humidity cell	May be performed on a selection of waste rock and ore samples if more realistic site-specific leaching rates (than humidity cells results) are desired (i.e. taking into account secondary minerals precipitation, on-site precipitation patterns etc.)
Sub-aqueous column (7.3)	Method to determine leaching rates from material deposited under water	Typically always performed on tailings samples and for waste rock subject to deposition under water
Intermittent bottle roll (7.4)	Method to determine leaching rates from material deposited under water but subjected to mechanical impact	Sometimes performed on waste rock, ore and tailings samples to predict drainage chemistry under prolonged mechanical impact e.g. in a stream
Pilot tests in the field (7.5)	Various methods measuring leaching from material subjected to deposition in the field	Not usually performed as part of the EIA work for mining projects in Greenland but may be required at a later stage

6. Static tests

Static tests refer to analyses or tests measuring the quality and quantity of different constituents in a sample at one point in time or during a very short time span (< approx. 24 h). The purpose of the static tests is to give an overview of relevant chemical properties of the materials. The information derived from static tests can form the basis for preliminary estimates of metal leaching and Acid Rock Drainage (ARD) potential of samples but does not give information on how the material will react over time on a long term basis (i.e. reaction rates, release rates of elements, time for onset of net acid production etc.). For this purpose, kinetic tests, which typically last for several months, are needed (Chapter 7).

6.1 Elemental analyses

The purpose of the elemental analyses is to obtain an overview of the elements that the samples contain and to highlight elements that are elevated in the samples e.g. compared to the average abundance in the Earth's crust (see Appendix 3 in Price 1997), and which could be of environmental concern. Combined with the results of the leaching tests, the elemental analyses can also be used to estimate the depletion time of elements in the samples during deposition.

Common methods for elemental analyses include:

- Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for solution analyses of major-, minor- and trace elements
- X-Ray Fluorescence (XRF) for whole-rock analyses of major elements
- Sulphur analyzers usually coupling a combustion furnace to an infrared gas detector for solid sample analyses of total sulphur and sulphur species.

A multi-element analysis by ICP-MS after a 'complete' (i.e. near-complete) acid digestion of the waste rock-, ore- and tailings samples is currently the preferred method for most elements. 'Complete' acid digestion typically involve a 3-(or 4-) acid digestion consisting of a mixture of hydrofluoric acid, hydrochloric acid and nitric acid (and perchloric acid in case of 4-acid digestion). Water samples should typically be analysed as a weak nitric acid solution (see Chapter 4.7 for sample preparation).

The analyses should as a minimum include the 60+ elements listed below equivalent to a full ICP-MS scan using a standard method and analyses of total sulphur and sulphur species (S^0 , S^{2-} , SO_4^{2-}) using an adequate technique (e.g. a Leco high temperature induction furnace system).

Below is a list of elements that can be measured using ICP-MS with some remarks:

- Lithium, beryllium, sodium, magnesium, aluminum, phosphorus, chlorine, potassium, calcium, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium (often used as internal standard), arsenic, selenium (often best measured as mass 78 in hydrogen-mode), rubidium, strontium, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium (often used as internal stand-

ard), palladium, silver, cadmium, indium (often used as internal standard), tin, antimony, tellurium, cesium, barium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, hafnium, tantalum, tungsten, rhenium, iridium (often used as internal standard), platinum, gold, mercury, thallium, lead, bismuth, thorium and uranium.

In addition, the analyses should include other elements and element species that may be particularly relevant to the project such as e.g. fluoride and radionuclides (if present and of environmental concern).

For water samples, also anions such as phosphate, nitrate, nitrite, sulphate and chloride, and other parameters such as alkalinity, may be relevant to measure depending on the project.

Relevant techniques for elements that can either not be measured, or for which the detection limits may be too high using ICP-MS, include:

- Ion Selective Electrodes (e.g. for fluoride analyses)
- Direct Combustion Mercury Analyzers (for precise and low-concentration mercury analyses)
- Ion Chromatography (for anions such as phosphate, nitrate, sulphate, chloride etc.)
- Alpha- and Gamma Spectrometry (for radionuclide analyses).

Below is a list of radionuclides that can be measured using alpha- and gamma spectrometry:

- Uranium-238, 235 and 234, thorium-232 and 230, radium-228 and 226, lead-210 and polonium-210.

For all analyses, proper quality assurance (QA) and quality control (QC) procedures should be followed, including the use of:

- Blank samples (to assess potential contamination from reagents etc.; usually concentrations in blank samples are subtracted from the samples)
- Duplicate samples (to assess the combined effect of the inhomogeneity of the samples and the analytical precision)
- Certified Reference Materials (to assess analytical accuracy and precision, including proper sample digestion).

The detection limit of the analyses should be calculated for each element based on the variation between the blank samples during the analyses e.g. as 3 times the standard deviations on the blanks.

The quality assurance/quality control (QA/QC) results should be documented in the laboratory reports along with the sample data.

Finally, to ensure the highest quality of the results, an accredited laboratory (ISO 17025 or similar) should be chosen to perform the analyses and the laboratory techniques and methods should comply with the Danish Environment and Food Ministry's requirements for measurements of environmental samples in force at the time of concern (Environment and Food Ministry, 2018).

6.2 Mineralogy

The potential leaching of elements from waste rock-, ore and tailings samples largely depends on how the elements are structured in minerals in the samples. Consequently, information of mineralogy is important for the assessment of the leaching potential of the samples and to interpret the results from the elemental analyses and the leaching tests. Detailed information on the mineralogy is especially relevant if ARD generation is a potential issue.

As an example, iron can occur in the acid generating mineral pyrite (Photo 2), in acid neutralizing calcium-iron carbonate minerals or/and as iron oxide minerals. Another example is fluoride, which can be present as highly soluble vil-laumite (sodium fluoride) or as the almost insoluble fluorite (calcium fluoride).

Photo 2. Waste rock from the former lead-zinc mine in Maarmorilik, West Greenland. Pyrite crystals (FeS_2), also sometimes referred to as 'fools gold', are clearly visible in the rock piece (Photo: Jens Søndergaard).



Consequently, information on the mineralogy of the samples should be provided, at least for a subset of samples representative of the range in geochemical composition of the geologic units and mine components (Chapter 3). Mineralogical analyses are required for the samples subjected to kinetic testing before and after testing (Chapter 6).

The most common techniques to obtain mineralogical data are:

- Visual descriptions
- Petrographic analysis
- X-Ray Diffraction (XRD) analysis (Rietveld method)
- Scanning Electron Microscopy coupled with Energy Dispersive X-Ray Spectroscopy (SEM/EDS)
- Electron Microprobe
- Laser Ablation and other microbeam analysis
- Image analysis
- Calculated mineralogy from solid phase elemental data.

Below is a brief description of each technique:

Visual descriptions of minerals in samples are typically performed by the field geologists during sampling. Visual descriptions are made with the aid of a hand lens and minerals may be identified from visual properties such as crystal habit, cleavage, fracture, luster, color and simple field procedures such as scratch tests for streak and mineral hardness as well as the hydrochloric acid fizz test for carbonate minerals. Further, a visual description can provide information on mineral association, distribution, grain size, hydrothermal alteration and weathering features including formations of secondary minerals on site. Finally, visual descriptions can provide information on large-scale geological variability such as structural features (such as fractures and veins), mineral associations with other minerals and different geologic units. Such large-scale geologic information based on visual descriptions can be valuable for interpreting mineralogical results from individual samples e.g. using more specialized techniques as described below.

Petrographic analysis involves a microscopic examination of the minerals using plane-polarized light on polished thin sections of the rock or from pulverized samples. Plane-polarized light can be transmitted through thin sections of most minerals (exceptions are most sulphide minerals, graphite, hematite and magnetite) and the optical properties of the minerals will assist in identification of the major and minor mineral phases, their shapes, grain size, spatial relationships and can provide an estimate of their relative proportions.

XRD analysis is currently considered one of the most cost-effective techniques for identification and quantification of minerals. Typically, samples are crushed and grinded to powder and either packed into a cavity in a holder or smeared wet onto a glass slide. Following an X-Ray beam scan, minerals are identified by comparison to locations and intensities of diffraction peaks of Mineral Reference Standards in a database. The Rietveld method for analyses of XRD data is a sophisticated method to further interpret the XRD data to improve accuracy and reduce detection limits and is highly recommended. Detection limits for minerals may be as low as 0.1 to 0.2 wt. % using the Rietveld method if there are no overlaps from peaks of other minerals.

Scanning Electron Microscopy coupled with Energy Dispersive X-Ray Spectroscopy (SEM/EDS) uses information derived from irradiation of samples with an electron beam and the subsequently measured backscattered electrons, secondary electrons and X-Rays to identify minerals, their grain size and arrangement of mineral grains and their elemental composition.

Electron Microprobe analysis, like SEM/EDS analysis, uses information derived from irradiation of samples with an electron beam but is used for very accurate and precise measurements of the element composition of mineral grains.

Laser Ablation analysis uses a laser beam to volatilize a small volume of the samples that can then be analyzed by e.g. ICP-MS for a large number of elements and provide information on the concentrations and isotopic composition. Other microbeam analyses include Proton Induced X-Ray Emission (PIXE) (for quantitative multi-element analyses), Secondary Ion Mass Spectrometry (SIMS) (for quantitative multi-element analyses and isotopic discrimination for some elements) and X-Ray Absorption Spectroscopy (EXAFS, XANES) (for information on oxidation states, types of bonding and adsorption modes).

Image analysis refers to further interpretation of SEM and Electron Microprobe results using dedicated image analysis software.

Calculated mineralogy from solid phase elemental data refer to calculations of mineral concentrations based on the total elemental composition (most often as maximum potential concentrations of individual minerals of concern (as e.g. pyrite) based on the mineral components).

Each of the techniques available for mineralogical analyses as described above has its strengths and weaknesses. Consequently, depending on the samples and minerals of concern, different mineralogical techniques may be appropriate. However, generally, the mineralogical data provided should at least include visual descriptions, petrographic analyses and XRD analyses.

6.3 Acid-base accounting

The acid-base accounting (ABA) test is a series of analyses and calculations commonly used as a screening tool to estimate the potential for samples to produce Acidic Rock Drainage (known as ARD) during weathering (Photo 3).

Photo 3. Acid Rock Drainage (ARD) from a coal mine waste rock pile in Svalbard. Precipitated iron hydroxides (also known as ochre) from oxidation of sulphide minerals (mainly pyrite) are visible on the ground surface. Note the pH of 2.68 in the water (Photo: Jens Søndergaard).



Primary sources for acid generation in mine waste during weathering include:

- Oxidation of sulphide minerals
- Dissolution of acidic sulphate minerals
- Hydrolysis of metals from sulphide and sulphate minerals.

Since ARD poses a common environmental threat associated with mining and since the ABA test has proven to be a cost-effective screening tool for ARD assessment, ABA should generally be performed on all waste rock-, ore- and tailings samples included in the geochemical test program.

From the ABA test, samples can be classified as either Potentially Acid Generating (PAG), Uncertain, or Non Potentially Acid Generating (Non-PAG) based on the balance between the sample's ability to generate acid i.e. the Acid Potential (AP) and the sample's ability to neutralize acid i.e. the Neutralization Potential (NP).

Several methods and modifications for ABA test exist, each with their own strengths and weaknesses. The method below briefly describes the modified 1996 Sobek method (MEND, 2009), which is perhaps the most commonly used method today:

The sample's AP is calculated from the sulphide-sulphur content of the sample using the following equation:

$$AP \left(kg \frac{CaCO_3}{t} \right) = \% \text{ sulphide} - \text{ sulphur} * 31.25$$

Using the equation above, it is implicitly assumed that only the sulphide minerals in the sample produce acid and that 2 moles of H⁺ is net produced per mole of sulphide (which is the case for complete oxidation of the most common sulphide-mineral, pyrite). However, variations between sulphide minerals exist spanning from sulphide minerals that do not produce acid (such as sphalerite, galena etc.) to sulphide minerals that produce up to 4 moles of H⁺ per mole of sulphide (such as arsenopyrite). Sometimes, the total sulphur content is used instead of only the sulphide-sulphur (as in the original 1978 Sobek method) in order to provide a more conservative estimate.

The sample's NP is measured by adding certain amounts of 1 N hydrochloric acid (HCl) (initially determined by a fizz test) gradually to 2 g of pulverized sample in a flask with distilled water to a pH of 2-2.5. The test is performed in room temperature, and after 24 hours, the sample solution is titrated with 0.5 or 1 N sodium hydroxide (NaOH) to a pH of 8.3.

The sample's NP is then calculated as:

$$NP \left(kg \frac{CaCO_3}{t} \right) = \frac{[N \times vol (ml)HCl] - [N \times vol (ml)NaOH] \times 50}{weight \ of \ sample \ (g)}$$

The balance between the AP and the NP can then be expressed as the Neutralization Potential Ratio (NPR) using the following calculation:

$$NPR = \frac{NP}{AP}$$

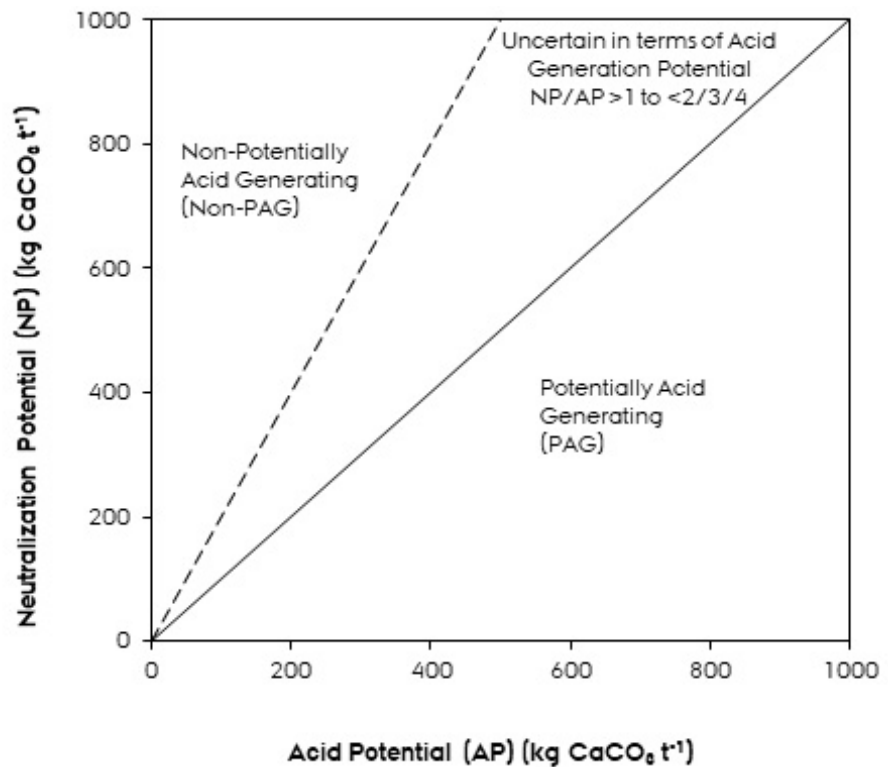
Based on the results, the following classification criteria can be used:

- If NPR < 1, the sample can be classified as PAG
- If NPR > 1 and < 2, 3, or 4 (varies in the literature depending on the confidence level used), the sample can be classified as 'Uncertain'
- If NPR > 2, 3 or 4, the sample can be classified as Non-PAG.

This is illustrated in Figure 1 below.

The ABA test provides a fast screening test for determination of the material's ability to generate ARD but does not e.g. provide any information of the effective AP and NP rates of the samples. Consequently, ABA tests should be followed up with more elaborate kinetic tests for representative samples (and sometimes also for outlier samples) classified as PAG and uncertain in term of ARD generation and coupled to detailed information of the chemical composition and mineralogy of the samples for subsequent predictions of the run-off chemistry.

Figure 1. Classification of samples according to their potential for generating acid based on their Acid Potential (AP) and Neutralization Potential (NP).



6.4 Net acid generation

Similar to ABA described above, the purpose of the net acid generation (NAG) test is to get an indication of whether a sample is net acid producing i.e. can potentially produce ARD.

The NAG and ABA tests both have their advantages and disadvantages and the two tests are often used in combination as screening tools for determination of ARD. Consequently, NAG tests should be considered for inclusion in the geochemical test program, especially for projects where ARD generation is likely.

The NAG test is based on direct measurement of the pH of a sample solution after complete oxidation of the sample using hydrogen peroxide as a strong oxidizing agent. This is opposed to the ABA test in which the acid potentially produced by sulphide oxidation is calculated based on the sulphide (or total sulfur) content.

Briefly, in the NAG test, 2.5 g of crushed sample (200 mesh; <75 μm) is subjected to 250 ml of 15% hydrogen peroxide, left overnight and heated and boiled shortly before the pH in the solution (i.e. the NAG pH) is measured. Based on the NAG pH, the following classification is usually used:

- Samples with a NAG pH > 4.5 is classified as Non-PAG
- Samples with a NAG pH < 4.5 is classified as PAG.

Subsequently, the solution can be filtered and an indication of the form of the acidity can be obtained by first titrating the solution to pH 4.5 and then continuing to pH 7.0. This final step can be useful for later interpretation of the results. The titration point of pH 4.5 includes acidity from free acid (i.e. sulphuric acid) and soluble iron and aluminum. The titration point of pH 7.0 also

includes metallic ions that precipitate as hydroxides at pH's between 4.5 and 7.0 as well as the acidity of hydrogen peroxide.

Several variations of the NAG test exist to accommodate a variety of geological materials. The three main variations are:

- Single addition NAG test
- Sequential addition NAG test
- Kinetic NAG test.

The single addition NAG test is most commonly used and is generally considered sufficient for complete oxidation of sulphide minerals in samples with less than 1% sulphur. The sequential NAG test (consisting of two or more single NAG tests) is used for samples with a higher sulphur content than 1% or for samples with a high content of other reactive materials that may affect the reactivity of the hydrogen peroxide such as organic material (e.g. coal). The kinetic NAG test is similar to the single addition NAG test, except that pH, temperature and sometimes EC are recorded during the test. This variation of the NAG test can be used to get an indication of the rates of sulphide oxidation, acid generation and acid neutralization (although less realistically than the long-term kinetic tests described later). Though the test is named 'kinetic' here, it is still considered a static test, because the test is conducted during a short timescale of less than 24 h.

Both the NAG and the ABA tests should only be regarded as screening tools and more elaborate kinetic testing (using tests closer representing real-world conditions and performed during a longer period of time i.e. months) should be performed on samples classified as PAG and uncertain in terms of ARD generation.

6.5 Paste pH_{1:2} and EC_{1:2}

The traditional paste pH_{1:2} and EC_{1:2} method is a recommended screening tool to assess the inherent acidity and salinity of the waste material when initially exposed to the environment in a waste disposal area. Consequently, paste pH_{1:2} and EC_{1:2} measurements should generally be done on all samples.

The paste pH_{1:2} and EC_{1:2} is determined by equilibrating the sample in deionised water for 12 –16 hours (or overnight) at a solid to water ratio of 1:2 (per weight unit).

For tailings, the sample should be used as it is without further crushing. Waste rock and ore samples, which are typically drill cores, should be crushed and the <250 µm fraction used.

6.6 Water leaching (Shake flask)

A number of different water leaching tests are available for assessing short-term leachability of constituents in waste materials exposed to water, each with their advantages and disadvantages.

Water leaching tests include: 1) Shake flask test (involving material in a flask shaken with deionized water for 24 h) (European Standards, 2002; MEND, 2009); 2) Synthetic Precipitation Leaching Procedure (involving material in a flask rotated end-over-end with a pH 4.2 water extract solution for 18 h)

(USEPA, 1994); and 3) Meteoric Water Mobility Procedure (a single pass 24 h column leach test using a water extract solution with a pH similar to the pH in precipitation of the geographical region of concern)(ASTM, 2013a).

Either of the tests above are considered acceptable, but the shake flask test is perhaps the most commonly test used and are recommended for mining projects in Greenland. Consequently, only shake flask tests will be described in the following.

The Shake flask test provide a method to assess the short-term leaching potential of the samples e.g. from leaching of elements from easily soluble minerals. Like the paste pH and EC method, the shake flask test gives an indication of the inherent acidity and salinity of the waste material. However, as opposed to the paste pH and EC method, in the shake flask test, this is quantified by a subsequent analysis of the element composition of the water and the sample is shaken for 24 hours to ensure full contact between water and solid sample surfaces.

Depending on the specific project and factors like the volume and composition of the geological materials, and number of samples collected in total, either all samples or a selection of samples should be subjected to water leaching tests (i.e. shake flask tests). If only a selection of the samples is subjected, those samples should be carefully selected based on data of the element composition, mineralogy, ABA, NAG and paste pH/EC measurements to represent both representative (near-mean/near-median) samples and samples which could be of environmental concern (samples with the highest concentration of specific elements of concern, potentially acid generating samples etc.).

Several standards for Shake flask tests exist, both European and Canadian (European Standards, 2002; MEND, 2009). Dissolution of soluble minerals in samples depends on a number of factors including time, liquid to solid ratio (L/S) and chemical composition of the water.

The European standard involve three different methods (EN 12457-1, EN 12457-2 and EN 12457-3) in which 175 g of sample material of less than 4 mm in size is shaken for 24 h in flasks using L/S's of 2, 10 and a combination of 2 and 8, respectively, and using deionized water.

The Canadian method uses 100 g of sample material of less than 6 mm in size shaken for 24 hours using a L/S of 3, and deionized water.

For mining projects in Greenland, either the European standard using a L/S of 2 (EN 12457-1) or the Canadian using a L/S of 3 is generally recommended. A L/S of 2 or 3 (as opposed to a L/S of 10) will increase the probability that most elements of concern will be above detection limits in the solution. Using a L/S of 10 would minimize the attainments of equilibrium (due to the solution being saturated) but would likely result in a number of elements that could not be measured accurately due to dilution. In addition, an L/S of 2 or 3 is considered more representative to situations in which rain or melt water percolates through a waste rock dump or ore stock pile.

As a supplement to deionized water used in the tests, a weak acid solution (e.g. at pH 4) can be used to assess the leaching if e.g. ARD occurs.

Shake flask solutions should be measured for the same elements as the other samples (see Chapter 6.1) in addition to pH, EC, temperature, oxygen and redox potential.

6.7 Sequential extraction

Sequential extraction tests can be used as a tool to assess the potential leaching of elements from the samples under varying environmental conditions and is generally required for a limited selection of samples representative of the waste rock, ore and tailings.

Of particular concern is enhanced leaching of most metals during acidic conditions and enhanced leaching of certain elements, such as iron and arsenic, under anaerobic conditions. Results from sequential extraction tests can be used to evaluate the robustness of the leaching predictions from other tests if the conditions differ from the test conditions. This can occur if ARD starts to be produced or if reducing conditions occur e.g. as the material is buried in the sediment in a lake or in the sea. Production of alkaline mine drainage can also enhance the mobility of some elements.

Several procedures for sequential extraction exist. A recommended and commonly used procedure is the three-step harmonized BCR[®] procedure (Sutherland, 2010). This procedure separates the elements in the samples into four fractions i.e. weak acid extractible- (using acetic acid for leaching), reducible- (using hydroxylamine hydrochloride for leaching), oxidizable- (using hydrogen peroxide for leaching) and residual fractions (hardly bound i.e. the remaining elements). This test is performed at room temperature.

The harmonized BCR[®] procedure has the advantage that it is well-described and can be performed in most laboratories due to little instrumentation required. In addition, a Certified Reference Material (CRM) (BCR-701) exists with certified values for a number of elements using the procedure. Consequently, the accuracy of measured results using the three-step harmonized BCR[®] procedure can always be evaluated if a sample of the BCR-701 CRM is included along with the samples and used for QC (recommended).

For further QC, it is also recommended to analyse the total element concentration in a subsamples not subjected to the sequential extraction procedure in order to check that the sum of all four fractions from the sequential extraction procedure equals the total concentration.

Sequential extraction solutions should be measured for the same elements as the other samples (see Chapter 6.1).

6.8 Radon release

Industrial activities such as mining for uranium and other elements/minerals, production of oil and gas, and combustion of coal can lead to elevated levels of naturally occurring radionuclides (NOR's) in the environment. NOR's here refer to uranium, thorium and their decay series (radium, radon, polonium, lead etc.). This is especially the case for improper management of generated material/waste.

Mine ore and generated mine waste such as tailings and waste rock that contain NOR's, and have a specific activity ≥ 1 Bq/g from individual radionuclides in

the uranium/thorium decay series, are classified as natural occurring radioactive material (NORM) (EAMRA, 2018a and b). NORM materials/wastes can potentially have a radiological impact on human health and the environment. An important pathway for potential radiological impact arise from the release of radon from NORM into the atmosphere. Radon is a radioactive gas produced from radioactive decay of radium in the uranium/thorium decay series. Here radon includes both radon from the uranium decay series and radon from the thorium decay series (although the latter is sometimes referred to as thoron). As a result, prediction, measurement and monitoring of radon release from NORM is necessary for assessment of the radiological impact and for investigation of any required mitigation actions.

Consequently, if the mining project includes NORM, radon release tests on representative samples of NORM should be made as part of the geochemical test program.

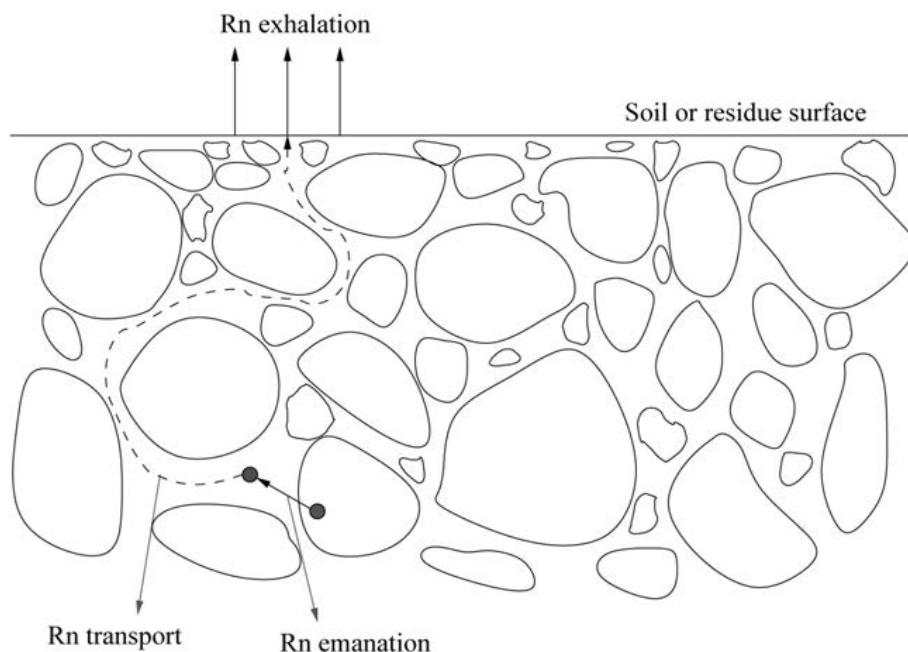
Briefly, production, transport and release of radon from ore/waste that contain NORM's can be described using the following terminology and is illustrated in Figure 2:

- **Emanation:** The radon emanation coefficient (also called radon emanating power) of the material is the fraction of radon atoms that escapes the solid material in which they are formed and become free to migrate through the bulk medium. By definition, the emanation power is dimensionless and the values range between 0 and 1. The emanation power depends on the uranium ore grade, the radium concentration and its distribution in the solid material, grain size, moisture content, temperature and the mineralogy of the material.
- **Transport:** The emanated radon in the pore space between the solid material grains can be transported within the material by diffusion and/or advection to the surface.
- **Exhalation:** The release of radon from the surface of the solid material (ore/waste) to the atmosphere per surface area/or weight unit per time unit (expressed as $\text{Bq m}^{-2} \text{ s}^{-1}$) is defined as the radon exhalation rate.

DCE and GINR recommend that mining projects in Greenland follow the recommendations given in IAEA (2013) for measuring radon emanation and diffusion coefficients, radon concentrations and exhalation rates for materials that are classified as NORM.

If radon release data from laboratory measurements are not available (e.g. during the initial licensing stage), predictive models should be used to evaluate the potential radiological impact of a new proposed project. Methods that should be used to estimate the release of radon from NORM materials are described in U.S. NRC (1987) and IAEA (2013).

Figure 2. Release of radon from solid materials to the atmosphere. Source: IAEA (2013).



6.9 Toxicity

Although not as such a geochemical test, toxicity tests using living organisms exposed to mine waste water are briefly mentioned here as they should be conducted on the same samples. In the following, toxicity tests are referred to as one of the static tests required and should be included when static tests are mentioned.

Toxicity tests have the advantage that it reflects the combined toxicological effect on selected relevant organisms of all the chemical components in the specific solution of concern (known as the 'cocktail-effect'). This provides information, which cannot be obtained theoretically. Toxicity tests are especially relevant for tailings supernatant, which often has a complex chemical composition incl. processing chemicals that potentially can be leaked. However, also mine water and drainage water from waste rocks dumps can be relevant to test depending on the specific project.

Toxicity testing is conducted in two ways; acute tests and chronic long-term tests. While acute toxicity effects are generally measured as lethality or behavior responses, long-term chronic effects often include mutagenic, carcinogenic and reproductive impacts. Acute toxicity tests are conducted on a dilution series of the test compound/solution and the aim is to identify the concentration of which the chemicals cause 50% lethality/effect (LC50/EC50, respectively) to the test organisms during a specific period of time (24 to 96 h). LC50 is the most frequently applied test for assessing effects of contaminants on aquatic organisms. Other acute toxicity studies are based on effects such as immobilization, respiration or other identifiable endpoints, rather than lethality, as more sensitive outputs. Long-term chronic toxicity effects are likewise conducted on a dilution series and most often the highest concentration by which the waste water causes no effect (NOEC) is reported as endpoint. A chemical is commonly classified as highly toxic when the acute LC50 toxicity is ≤ 1 mg/l or when long-term toxicity indicated as NOEC is ≤ 0.1 mg/l (ECHA, 2015). Another relevant measure is the LOEC value, which is the lowest concentration that causes an effect on the test organisms.

For mining projects in Greenland, toxicity tests involving standardized ecotoxicological tests using algae, crustaceans and fish as test organisms should be made on a dilution series of potential leaching water that could be of environmental concern. It is highly important to take into consideration that the degradation of chemicals may be slower under arctic conditions than under temperate conditions and that bioaccumulation may be higher. Tests should therefore be preferably be performed under arctic conditions (e.g. low temperatures) and with species present in the Arctic. Both acute and chronic toxicity effects should be investigated and dose-response curves should be made. The tests should be conducted on a number of representative samples and for a minimum of three replicates.

Also, available ecological toxicity data for all planned processing chemicals in the project should be supplied (see also Bach et al., 2016).

7. Kinetic tests

Kinetic tests refer to tests that are conducted over long period of time (typically months) and allow for ongoing measurements of kinetic properties of the samples. Information that can potentially be obtained from kinetic tests include:

- Weathering rates of minerals and release rates of elements
- Rates of acid generation and neutralization
- Time to onset of net acid conditions
- Depletion of soluble and oxidizable elements in the samples over time.

Consequently, kinetic tests are an important part of most geochemical test programs and are required for most mining projects in Greenland. The extent of the kinetic testing required will depend on factors such as the geological materials and inherent environmental issues of concern as well as specific project-related factors such as the volume of waste material and the chosen method of deposition.

Several kinetic test types exist, which are designed to simulate deposition of materials under different conditions e.g. waste rock and ore deposited on land under well-flushed aerated conditions and tailings deposition under water in a tailings dam. Redox potential (Eh) and pH are also important key variables with respect to conditions for mineral weathering and element release. Consequently, careful consideration should be made with respect to selection of the kinetic tests for specific sample types to address the specific prediction questions of concern, and to simulate deposition conditions in the field as close as possible.

Since kinetic tests are time-consuming and costly, kinetic tests are typically performed only on a selection of samples, which is chosen based on results from the initial static tests. Samples for kinetic testing should generally include samples representative of the bulk material from each waste type as well as representative samples from subunits, which can potentially cause environmental problems (i.e. 'high concentration samples', potentially acid generating samples etc.).

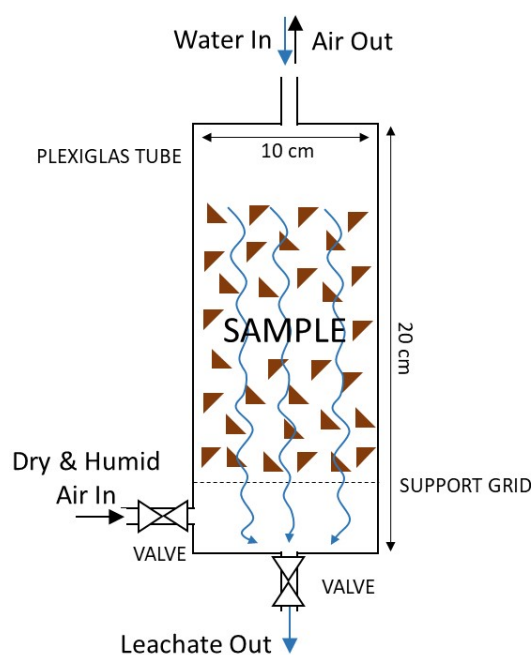
For all kinetic tests, it is important to characterize the samples using comprehensive static testing on subsamples both before and after the tests have been completed in order to identify changes in the solid phase characteristics (e.g. depletion of soluble minerals) during the tests.

7.1 Humidity cell

The Humidity cell (HC) test is the most commonly performed kinetic test. The HC test is a laboratory-based accelerated weathering test used to simulate mineral weathering and release of weathering products (i.e. elements) under aerated and well-flushed conditions (i.e. with minimum precipitation of secondary minerals). Consequently, HC tests are usually the recommended kinetic test for testing of waste rock and ore for deposition on land. HC tests are also sometimes conducted on tailings, which can provide some valuable information. However, since tailings should always be deposited under cover (water or clay), the sub-aqueous column test (Chapter 7.3), or similar, is generally the preferred kinetic test for tailings.

The HC test is the only kinetic test that is standardized, and the test protocol for the HC test is described in detail in ASTM D5744-13E1 (ASTM, 2013b). Briefly, 1 kg of sample crushed to less than 6 mm (1/4 inch) in size is put into a Plexiglas test column as outlined in Figure 3. The column is then subjected to initial flushing and collection of leach water (Day 0) and weekly cycles of pumping dry air (Day 1-3) and humid air (Day 4-6) through the column following by flushing and collection of leach water (using 500 ml deionized water allowed to soak through the column for at least 2 h) at Day 7. The test is performed in room temperature. The weekly cycles are continued for at least 20 weeks and until stable release rates are observed (often more than 40 weeks is required to obtain stable release rates). Stable rates should be observed for at least 5 weeks (Bouzahzah et al., 2015). If ARD is a potential issue, HC tests may be continued until the onset of net acid generation (sometimes for years).

Figure 3. Principle of the Humidity cell test.



The leach water from the weekly leaching is subsequently filtered and analyzed for the basic electrochemical parameters: pH, electrical conductivity and redox potential in addition to alkalinity, acidity, dissolved anions (sulfate etc.) and total dissolved element composition (Chapter 6.1). A full suite of analysis is required (as least for part of the leach water samples) for subsequent geochemical modelling of secondary mineral precipitation etc.

A great advantage of the HC test is that it is standardized and widely used and therefore allow for a comparison of HC test results and later observations of resulting drainage chemistry between projects/sites world-wide.

The HC test is widely considered an accepted procedure for determining sulphide mineral oxidation rates and for prediction of the lag time to onset of acidification within granular mining wastes i.e. waste rocks and ore residues.

Based on collection and analyses of the leach water, primary mineral weathering and element release rates (per kg sample) can be assessed at different times during the test.

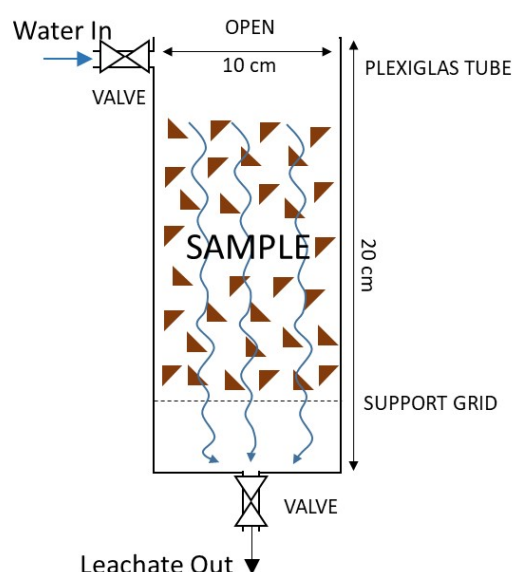
Due to typically more well-flushed conditions in the HC test than in the field, HC test results may, however, underestimate secondary mineral precipitation (such as iron-hydroxides, gypsum and jarosite), which often occur in the field. This factor should be taken into consideration when later interpreting the HC test results and can be evaluated using geochemical equilibrium modelling.

If a more realistic drainage water prediction is the objective (i.e. taking into account secondary mineral precipitation and dissolution), the sub-aerial column test (Chapter 6.2) may also be used e.g. in combination with the HC tests.

7.2 Sub-aerial column

The sub-aerial column (SAEC) test is a variation of the HC test but there is no pumping of dry and moist air through the column and the column is just left open in the top. No standardized procedure for this test exists but the principle is outlined in Figure 4.

Figure 4. Principle of the Sub-aerial column test.



Typically, the column is flushed using water volumes and flushing intervals likely to be encountered in the field and in temperatures closer resembling field conditions. Also, water with a composition more similar to water at the deposition site can be used (as opposed to the deionized or MilliQ water used in the HC tests). The objective is to simulate the net impact of both primary mineral weathering and potential secondary mineral precipitation/dissolution on the drainage water likely to be encountered in the field. Consequently, the SAEC test is likely to provide more realistic drainage water chemistry predictions but lacks standardization, and since it is less well aerated and flushed, usually it takes longer than HC tests to perform until stable release rates are reached.

The same duration and leach water treatment and analyses as for the HC test is typically used for the SAEC test.

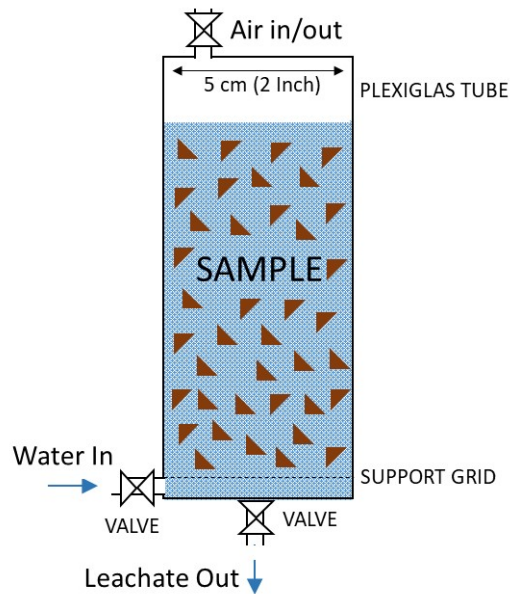
7.3 Sub-aqueous column

The sub-aqueous column (SAQC) test is a laboratory based kinetic test designed to simulate release of elements from waste materials when deposited

under water. This test is usually recommended for mining projects in Greenland for assessing release of elements from tailings when disposed under water e.g. in a tailings dam.

Typically, a sample of approximately 2 kg of e.g. tailings (without further particle size reduction) is put into a long, thin Plexiglas test column as outlined in Figure 5 (or a near-similar design). Subsequently, leach water is collected, filtered and analyzed at certain time intervals similarly to the HC test.

Figure 5. Example of a sub-aqueous column test design.



For leach water, deionised water is typically used for the SAQC test, sometimes in addition to process water or leach liquor if tailings are tested (i.e. for flotation tailings and chemical residue tailings, respectively).

SAQC tests can be conducted at room temperature or a temperature close to the mean air temperature at the site e.g. at 5°C.

Typically, SAQC tests are conducted during several months (e.g. 6 months) and leach water is collected and replaced at short intervals (e.g. daily) in the beginning and at long intervals (e.g. monthly) in the end.

7.4 Intermittent bottle roll

The intermittent bottle roll (IBR) test is a laboratory based kinetic test designed to simulate weathering and release of elements from waste materials during transport in streams i.e. under water during prolonged mechanical impact. The test can provide valuable information on the leaching of elements in the event that the waste material is released and transported in the aquatic environment and is sometimes recommended for mining projects in Greenland, depending on the specific project.

In the IBR test, a bottle with deionized water and the waste material e.g. waste rock or ore is rolled consistently over a period of e.g. 6 months. Typically approximately 1 kg of solid material and a L/S of 2 is used. Leach water is subsequently collected and analyzed at different time intervals during the test, most often in the beginning (typically for the same parameters as the HC test, Chapter 7.1). If tailings is tested, ionized water is often replaced with solutions

more similar to the real solutions i.e. using process water and leach liquor for floatation tailings and chemical residue tailings, respectively.

7.5 Pilot scale tests in the field

In addition to the above-mentioned kinetic tests, which are all conducted in the laboratory, field based kinetic tests (i.e. pilot scale tests) may be a good option. Field based kinetic tests are likely to provide more realistic drainage chemistry results since site specific temperatures, precipitation patterns etc. is used but are usually also more time-consuming, logistically difficult and expensive to conduct. Consequently, field based tests are most relevant if environmental problems associated with deposition of the waste materials are likely and/or if site specific conditions cause great uncertainties in the laboratory-based estimates.

Field based kinetic tests range from barrels or lysimeters containing waste materials to mine walls and test piles of e.g. waste rock or ore, all connected to a system for collecting leach water for subsequent analyses.

Field based kinetic tests are not usually required as part of the EIA work for mining projects in Greenland but may be required at a later stage.

8. Interpretation of test results and model predictions

With respect to interpretation of test results, results from the static tests should be combined to provide an overview of the composition and basic properties of the waste rock, ore and tailings from the project.

Important things to consider when evaluating the static test results include:

- Do the materials contain elements in anomalous high concentrations compared to the average Earth's crust (Appendix 3 in Price (1997) can be useful) or elements of special environmental concern?
- How is the mineralogical composition of the materials? Special focus should be on sulphur-containing minerals (such as pyrite), minerals known to be easy soluble (such as villiaumite) and minerals containing elements in anomalous high concentrations or of special environmental concern at the site.
- What is the net acid (or base) generation potential of the materials (evaluated based on the acid-base accounting -, net acid generation - and paste pH and EC tests combined with results from elemental- and mineralogical analyses)?
- Is generation of ARD a potential issue at the site?
- What about neutral or alkaline mine drainage issues (less common than ARD but can pose significant environmental problems, see e.g. Heikkinen et al., 2009 and Gonzalez et al., 2012)?
- What is the short-term leachability of elements in the materials (evaluated based on water leaching tests)?
- What are the leachability of elements under different environmental conditions i.e. how will e.g. ARD and changes in redox conditions influence the leaching (evaluated based on the sequential extraction tests)?
- If the materials contain radioactive minerals, what will be the total release of radon (evaluated based on the radon release tests)?
- What is the expected toxicity of drainage water from the materials (evaluated based on the toxicity tests)?

In addition to answering these questions, results of the static tests should be used to select samples for subsequent kinetic tests. An adequate selection of samples for kinetic tests will depend on the specific project, the material properties and the prediction questions being asked but should generally include samples representative of the bulk material from each waste type (i.e. 'near-mean concentration' samples) as well as representative samples from subunits, which can potentially cause environmental problems ('high concentration samples', potentially acid generating samples etc.).

Once the appropriate kinetic tests have been conducted, test results should be included in model predictions of the drainage water chemistry at the site, which should be part of the EIA. These predictions should take the actual volumes of waste rock, ore and tailings planned for the project each year into account in order to make model predictions on an annual basis during the lifetime of the mine and after closure.

There is no fixed or single commonly accepted method to apply when upscaling results from small-scale laboratory based kinetic tests to full-scale mining components. However, it is important that all important factors potentially influencing the drainage water chemistry on site are taken into account and that all calculations and assumptions are transparent, well described and valid.

Factors that can influence upscaling from the small-scale laboratory based kinetic tests to full-scale site specific field conditions include:

- Particle size (and hence surface area exposed to chemical reactions per mass of material)
- Temperature (keep in mind that temperatures inside e.g. waste piles can sometimes be significantly higher than outside air temperatures (Photo 4))
- Availability of oxygen
- Availability of water, including:
 - Volume of water flow (based on precipitation/infiltration)
 - Time between infiltration events
 - Water residence time in the deposit
 - Percentage of rock in the deposit flushed by the water flow
- Differences of pH in leaching water
- Potential accumulation of weathering products during dry periods and winter (relevant for waste rock and ore stock piles) and flushes during rain events and spring thaw (Photo 4))
- Chemical interaction between water and particles
- Precipitation/dissolution of secondary minerals
- Dilution of drainage water from streams, in lakes/dams etc.

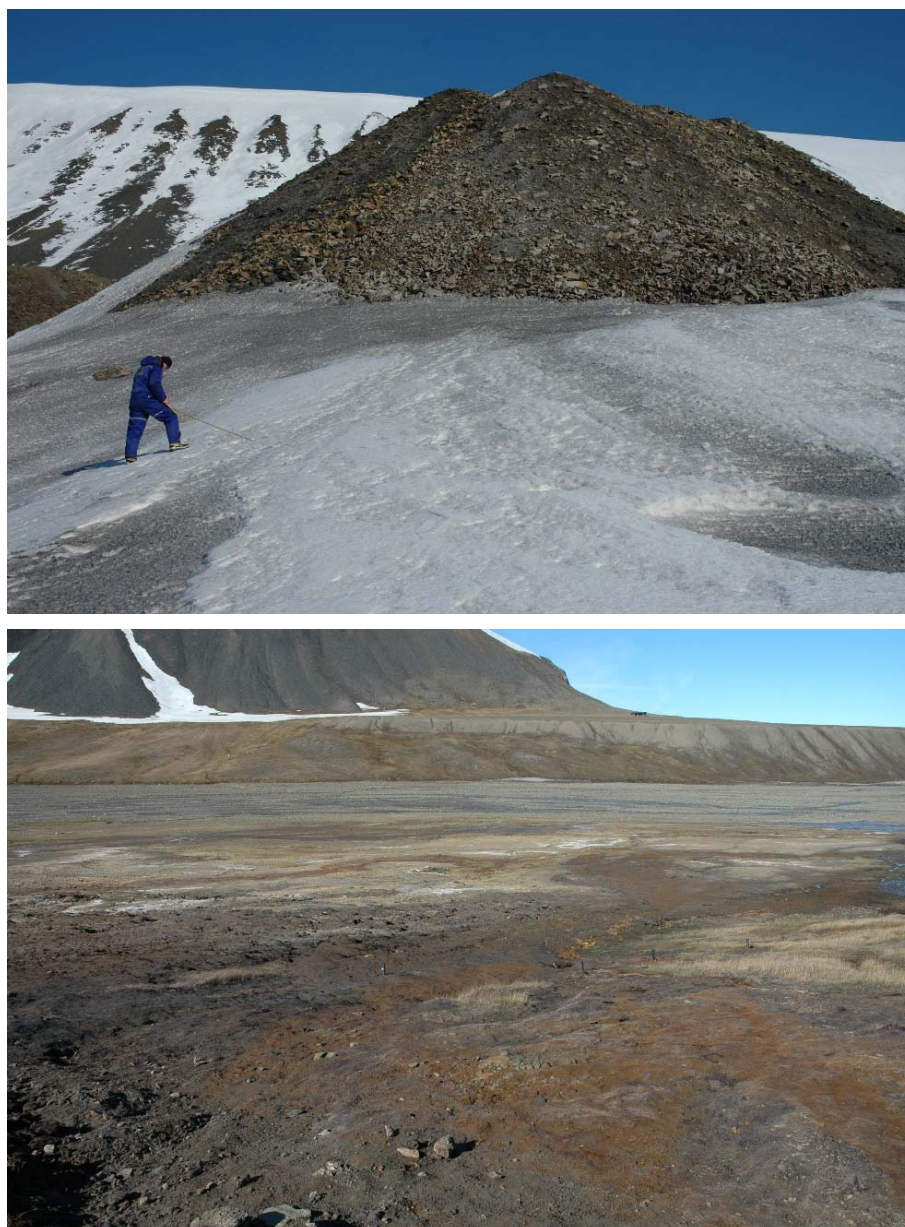
Of the factors above, the difference in particle size between the test samples and the full-scale waste rock is the most commonly used individual scaling factor. Kinetic tests are usually performed on test samples crushed to <6 mm in size and the exposed surface area of the particles in the sample can be described using a detailed size fraction analyses and/or direct measurements of the surface area using the BET technique (see Chapter 4.7). However, the particles size distribution and surface area of the full-scale waste rock is more difficult to determine or predict accurately, especially during the EIA stage of a mining project, when little or no real waste rock has been generated. For guidance and in case no detailed data exists, the common percentage of the <6 mm size fraction in waste rock after blasting ranges between 3 and 20% depending on blasting technique, rock characteristics etc. according to Morin (2013). The numbers were derived from a detailed study of 78 datasets of full-scale mine waste rock fractions gathered in Sanchidrián et al. (2012).

As an alternative to including all factors potentially contributing to the upscaling of small-scale laboratory based kinetic tests into full-scale field conditions separately in the calculations, an empirically based 'Cumulative Scaling Factor (CSF)' based on observations at comparable sites can be used. This is described in previous work by the Canadian Minesite Drainage Assessment Group (MDAG) and reported in Morin (2013). In Morin (2013), a CSF of 0.05-0.60 was reported as typical based on observations from a range of mine sites (i.e. the larger scale rates were typically 5-60% of the small scale rates).

When subsequently applying the kinetic test results in the predictions, it is important to include both the initial leaching (which typically occur at the highest rate) and the long-term leaching. Often, the average weekly leaching rate for the duration of humidity test is used as the weekly rate during the

first year (multiplied by a scaling factor(s)) and the average of the last measurements of the humidity cell tests is used for the following years.

Photo 4. Predicting drainage from mine waste in the Arctic can be especially challenging. Here a coal mine waste rock pile in Svalbard during winter (upper photo). Despite an average air temperature of -5°C and winter temperatures down to -30°C , the core of the pile was surprisingly warm and constantly at $+5^{\circ}\text{C}$ year round due to heat-producing oxidation processes (mainly oxidation of pyrite). Consequently, oxidation processes continued in the pile during winter and pollutants were released as a flush during a 2-3 week period of thaw in early spring with very high metal concentration and low pH levels in the drainage water. The rest of the summer showing low levels of pollutants in the drainage water. The lower photo shows the vegetation damage downstream from the pile due to Acid Rock Drainage (ARD) release (Photos: Jens Søndergaard).



Predictions should include all elements measured in the leaching solutions.

Predictions should both reflect the most likely scenario using representative samples but also take into account the statistical variability of geochemical properties observed during both static and kinetic tests to make e.g. a 95% confidence interval of the predictions or a conservative (worst case) estimate based on the highest leaching samples.

If ARD is a potential issue, results from the kinetic tests should be used to estimate the time to onset of net acidic conditions.

If easy soluble minerals are present, results from the kinetic test should be used to calculate solid phase depletion times for the minerals during deposition.

If radioactive minerals are present, release of radon and other radionuclides should be included in overall radiological assessment of the project. Details of this radiological assessment will not be treated in these recommendations but will be provided on a case by case basis.

Finally, the predicted drainage water chemistry from all the mine components i.e. the waste rock and ore stock piles, in mine pits and in tailings dams should be compared to Greenland Water Quality Criteria for mining activities (Mineral Resources Authority, 2015), and to other relevant water quality criteria when appropriate, and the predicted environmental impact assessed based on that comparison and included in the EIA.

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GEOCHEMICAL TEST WORK IN ENVIRONMENTAL IMPACT ASSESSMENTS FOR MINING PROJECTS IN GREENLAND

– Recommendations by DCE and GINR

This report by Danish Centre for Environment and Energy (DCE) and Greenland Institute for Natural Resources (GINR) provides background information and a set of recommendations for geochemical test work required for Environmental Impact Assessments (EIAs) for mining projects in Greenland. The report includes specific recommendations for identification and characterization of rock and waste units, description of mine components, collection of samples, selection of test methods, interpretation of test results, predictions and reporting. Further, the report includes recommendations for a work flow that will enable an improved time-efficient dialogue between the companies, the authorities and its advisors regarding the requirements for geochemical test work, interpretation of the results and finally inclusion of the predictions in the EIA.

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