



TAILSAFE

Sustainable Improvement in Safety of Tailings Facilities
TAILSAFE

A European Research and Technological Development Project
Fifth European Community Framework Programme
Energy, Environment and Sustainable Development (EESD)

Contract Number: EVG1-CT-2002-00066

Website: <http://www.tailsafe.com/>

Catalogue of Site Characterisation Criteria

- Requirements for an Adequate Site Characterisation of Tailings Facilities -

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Karlsruhe, May 2004

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1 INTRODUCTION

The prime function of a tailings storage facility is the safe, long-term storage of tailings with minimal environmental impact. At this, site characterisation is the first step towards risk assessment with the intention of sustainable environmental protection. The role of site characterisation in relation to the overall investigation (e.g., risk assessment) is illustrated in Fig. 1.

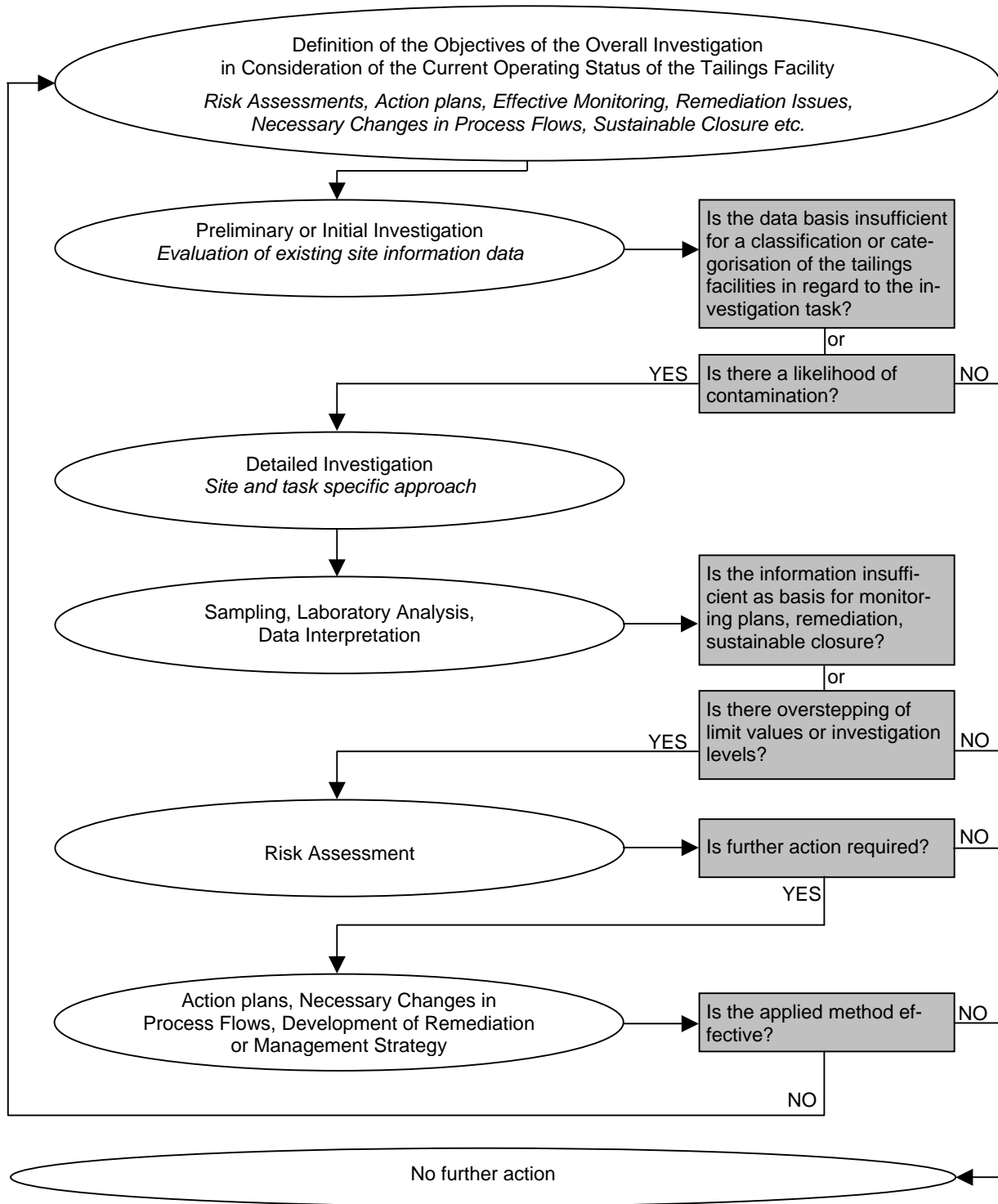


Fig. 1: Site characterisation in connection to the overall investigation.

Site characterisation, based on an accurate and enfolding data collection, provides the opportunity for identifying betimes potential risks emanating from tailings facilities and sources of environmental contamination. A comprehensive site characterisation is divided into two main phases:

1. Evaluation of existing site information data - preliminary or initial investigation
2. Site specific approach - detailed investigation

This concept paper gives an overview on currently used methodology and techniques and other issues concerning

- potential dangers emanating from tailings facilities,
- principles of site investigation,
- data quality assurance requirements,
- field work, including soil sampling,
- laboratory analysis,
- basics of data interpretation,

and should be used as a source for individual selection of reasonable investigation and analytic methods to obtain the necessary data with respect to the particular objectives of the site characterisation. The paper is one of the outcomes of Workpackage 6 of the European research project "Sustainable Improvement in Safety of Tailings Facilities" (TAILSAFE).

1.1 RISKS EMANATING FROM TAILINGS FACILITIES

An adequate site characterisation is the basis of a sustainable risk assessment and risk management, respectively. Therefore, the investigation has to take into account all potential environmental impacts from tailings facilities. Emissions (spreading along water-, air- and bio-pathways) from tailings can be toxic and in many ways hazardous to biota and humans. Knowledge on the origin and emergence of environmental contamination is an important input for the correct interpretation of data and evaluation of potential risks. Some aspects of environmental risks are:

- Acid Drainage

Referred to as acid rock drainage (ARD) or acid mine drainage (AMD). Acid drainage (AD) generates from tailings respectively mine waste rock (i.e. ARD) or mine structures like pits (i.e. AMD) and is associated with sulfide ore bodies mined for, e.g., Pb, Zn, Cu, or Au. Materials, that contain iron sulfide minerals such as pyrite, can generate acidity when exposed to moisture and an oxidant (oxygen from the atmosphere or from a chemical source, for instance ferric iron). The amount of acid drainage is therefore primarily a function of the mineralogy of the rock material and the availability of water and oxygen.

The rate at which acid is generated depends on the composition of the sulfide minerals, their crystal size, and shape and the presence of reaction coatings that may form on the surfaces of sulfide minerals. Acid generation comprises a complex set of chemical reactions that change through time. The potential of acid generation competes with the potential of acid neutralization. Acid neutralization reactions are enabled by a number of minerals such as calcium- and magnesium-bearing carbonates and oxides/hydroxides of calcium, magnesium and aluminium (EPA 2003).

Dissolved metals in acid drainage, such as lead, copper, silver, manganese, cadmium, iron, zinc, arsenic, etc., can disable surface water and groundwater as drinking water or aquatic habitat, and may lead to accumulation in sediments and bioaccumulation of these metals. An other important environmental aspect to be taken into consideration is that acid generation not yet occurred at a spe-

cific site can still occur in the future after changes in the site conditions (e.g., running dry of the covering water, surface erosion, rainfall infiltration) and may then last over long periods of time.

The potential of tailings to generate acidity and mobilise heavy metals depends on different site-specific factors, such as:

- Generation factors,
which determine the ability of the material to produce acid (availability of water, oxygen and certain iron- and sulfur-oxidizing bacteria as active agents).
- Chemical control factors,
which influence the products of oxidation reaction (mobilise metal ions respectively immobilise them by, e.g., ion exchange on clay particles or neutralize the acid by alkalinity).
- Physical factors,
which are important for the acid generation potential (physical characteristics of the waste, such as particle size and permeability, local hydrology and climate, physical weathering characteristics).

Therefore, the characteristic of the acid drainage production depends on different local conditions and parameters such as:

- physical and chemical material characteristic,
- infiltration and evaporation rate,
- variability of available oxygen with depth,
- design of the pond and dam,
- heterogeneity of the site.

- Metal Contamination of Soils, Aquifers and Surface Water

Dissolved pollutants are primarily metals, but may include sulfates, nitrates, and radionuclides. These contaminants can migrate from tailings ponds to local groundwater and surface water and thus also potentially contaminate soil. Some toxic substances (e.g., lead and mercury) may also be found at elevated levels in sediments, while not being detected or being detected at much lower concentrations in the water column. High metal concentrations can have acute and chronic effects on biota. Metal mobilisation not only occurs under low pH conditions, as caused by acid drainage, but there is also increasing concern about neutral and high pH metal mobilisation (EPA 2000a).

Sources of these pollutants are:

- Mined ore that not only contains the target mineral but varying concentrations of a wide range of other metals (such as the highly toxic Cd in Zn ores).
- Chemicals used in mining and beneficiation, such as copper, zinc, chromium, cyanide, nitrate, phenolic compounds and sulfuric acid.

- Radioactivity of tailings facilities

Tailings with increased radioactivity may not only be generated by uranium ore processing, but also by the processing of ore material with a natural radionuclide content and resultant accumulation effects (e.g. sorption at suspended particles). Relevant radionuclides are:

- potassium-40;
- intermediate products of uranium and thorium radioactive chains, like the highly radiotoxic radium and the radioactive inert gas radon.

Release pathways of environmental contamination can be seepage water and, in the case of radon, also direct diffusion from solid to the atmosphere (ATV-DVWK 2001).

- Dispersion of Eroded Contaminated Material

The main factors influencing water erosion, by which potential contaminated soil particles are detached, suspended, transported and deposited at a different location, are runoff velocity and runoff volume which are dependent on:

- amount of rainfall/snowmelt runoff,
- soil infiltration rate,
- soil texture and structure,
- vegetation cover,
- length and angle of slope,
- implementation of erosion control practices.

Wind erosion and downwind deposition of tailings material occurs particularly when the waste material dries up after closure/abandonment or when it is used for dam construction. The tailings material, then released as wind-driven dust, contaminates areas downwind, as coarse particles settle out of suspension in the air. Therefore, in the case of remediation aims, the downwind area must also be addressed.

- Auto-ignition

Tailings facilities of coal mining activity hold the risk of auto-ignition caused by oxidative reaction and associated material warming-up (ATV-DVWK 2001).

- Exhaust gases

Microbiological decomposition in a reducing milieu may produce CH₄, H₂ and CO₂. Low pH-values may cause the occurrence of hydrogen sulfide (H₂S) as gaseous decomposition product.

- Structural failure

Pollution risk emanating from tailings facilities also results from structural failure and a subsequent release of contaminants. This can have short-term effects (such as flash floods including widespread contamination or cut-off of infrastructure) and long-term effects (such as contamination of soils, bioaccumulation of metals, biota dieing off, etc.).

The risks and the potential hazards related to dam failures are associated with the design (upstream method, downstream method, etc.), the physical configuration, the continuity in construction, proper internal drainage, sufficient flood storage capacity, and how the local conditions, such as geology, topography, climate etc., have been taken into consideration when planning the facility. Structural stability also depends on the physical characteristics of the used construction materials, which are usually the coarse, dried out tailings. Modern tailings impoundments are normally lined to prevent seepage, but this is not always the case at historic mine sites. Hydrostatic pressure within and behind the embankment may result in a partial or complete failure of the structure.

There are a number of common failure modes to which tailings impoundments may be vulnerable. Failure modes which may result in partial or complete embankment failure are (EPA 1994):

- Rotational slide

The failure surface appears as a segment of a horizontal cylinder. Slope failures may range from local sloughing of tailings at random areas along the face of an embankment to massive circular arc slides extending over the entire structure. Instability occurs when the shear stress on the failure surface equals the shear strength (VICK 1983).

- Foundation failure
A weak layer of soil or rock existing at shallow depth below the impoundment may fail and cause a movement along a failure plane.
- Internal erosion by seepage
Internal erosion of tailings dam material may occur resulting from seepage of leachate. The seepage may be caused by, e.g., inadequate drainage measures or dam defects, such as settlement cracking or poor compaction of fill (ICOLD / UNEP 1996c).
- External erosion
Wind and water erosion of tailings material causes not only the dispersion of contaminated material but can result in destabilisation of the tailings dams structure (ICOLD / UNEP 1996c).
- Overtopping
Overtopping typically results from inadequate hydrogeological or hydraulic design. The friction caused by rapid flow over an unprotected embankment may quickly erode a trench in the dam's material, with the effect of continuing release of potentially hazardous material.
- Liquefaction
Tailings impoundments typically contain unconsolidated, saturated deposits of similarly-sized grains, which are susceptible to temporary suspension in water (VICK 1990). Factors affecting the potential for liquefaction include grain size distribution, relative density or compactness, location of the water table, and in the case of dynamic stress the intensity and duration of ground shaking.

1.2 ENVIRONMENTAL IMPACT OF TAILINGS FACILITIES

The appearance of potentially toxic substances in tailings materials pose a special risk for human health and the environment in general. Hazardous effects on the environment emanating from such substances not only depend on their concentration, but also on the local conditions (pH, temperature, etc.). The variety of relevant parameters leads to a complex scenario that has to be taken into consideration.

Tailings have been subjected to physical or physico-chemical separation processes (e.g. flotation), chemical solution processes (e.g. cyanidation), or have been formed by a chemical process (e.g. acid digestion or combustion). Examples of remnant process chemicals are (ICOLD 1996a):

- caustic from the extraction of bauxite,
- cyanide from the extraction of gold,
- organic foaming agents from flotation processes,
- phosphoric acid from fertiliser manufacture.

Some reagents (e.g., cyanides, frothers, xanthates) require long retention time, oxidative conditions (air, bacteria, sunlight), and in some cases elevated temperatures (e.g., xanthates above 30°C) to decompose (EUROPEAN COMMISSION 2003 - BAT).

Some selected toxic substances and their resultant potential environmental impacts are (especially toxic species in brackets; data from ATV-DVWK 2001 except for cyanide):

- Aluminium (Al^{3+})
highly phytotoxic, fish poison
- Arsenic (As^{3+} , As^{5+})
toxic to humans
- Beryllium (Be^{2+})
toxic to humans, heavy fish poison

- Cadmium (Cd^{2+})
toxic to humans, heavy fish poison
- Chromium (Cr^{3+} , Cr^{6+})
toxic to humans
- Cyanide
Cyanide can cause three major types of impacts:
 - Tailings ponds with a free surface of cyanide containing water can present an acute hazard to wildlife and birds. In the case of abandoned mines, acute cyanide toxicity should not be of concern.
 - Spills of cyanide solution or cyanide leachate reaching surface water or ground water can cause short-term (e.g., fish kills) or long-term (e.g., contamination of drinking water resources) impacts.
 - Cyanide may also increase the potential for metals mobilisation (EPA 2000a).

Cyanide can be strongly complexed with iron then presenting a much lower environmental risk. The stability of such complexes over long periods is not well understood and should be studied particularly regarding sustainable closure of tailings facilities.
- Lead (Pb^{2+})
toxic to humans, strong fish poison
- Mercury (Hg^{2+})
toxic to humans, food chain accumulation
- Selenium (Se^{4+} , Se^{6+})
highly toxic

The following listing (Table 1) shows effects on humans, animals and plants of some metals.

Tab. 1: Effects of some metals on humans, animals and plants (EUROPEAN COMMISSION 2003, after VICK 1990).

Metal	Effect
Arsenic (As)	Highly poisonous and possibly carcinogenic in humans. Arsenic poisoning can range from chronic to severe and may be cumulative and lethal.
Cadmium (Cd)	Cadmium is concentrated in tissue and humans can be poisoned by contaminated food, especially fish. Cd may be linked to renal arterial hypertension and can cause violent nausea. Cd accumulates in liver and kidney tissue. It depresses growth of some crops and is accumulated in plant tissue.
Chromium (Cr)	Cr+6 is toxic to humans and can induce skin sensitisations. Human tolerance of Cr+3 has not been determined.
Lead (Pb)	A cumulative body poison in humans and livestock. Humans may suffer acute or chronic toxicity. Young children are especially susceptible.
Mercury (Hg)	Hg is biologically magnified, accumulating in the brain, liver and kidneys of animals. Hg poisoning may be acute or chronic.
Copper (Cu)	Small amounts are considered non-toxic and necessary for human metabolism. However, large doses may induce vomiting or liver damage. Toxic to fish and aquatic life at low levels.
Iron (Fe)	Essentially non-toxic but causes taste problems in water.
Manganese (Mn)	Affects water taste and may stain laundry. Toxic to animals at high concentrations.
Zinc (Zn)	May affect water taste at high levels. Toxic to some plants and fish.

2 PHASE 1: PRELIMINARY INVESTIGATION - EVALUATION OF EXISTING DATA

The main objective of the preliminary site study is to provide elementary background information for an initial conceptual site model. This part of the investigation is essential for all types of sites and questions. Consideration of all available site information, as far as practicable, minimises the number of necessary site visits and consequently the associated cost. As a matter of course, some existing data must be confirmed and completed by site inspections.

Sources of existing site data information are, e.g., historical and actual aerial photography, satellite imagery, maps, past surveys, operational records, interviews with owners, operators and workers, local residents, and local regulatory agencies.

2.1 SITE IDENTIFICATION

The first step towards an exhaustive report of the site characterisation is compiling general site information regarding responsibilities, licences of the facility and dimensions of the area under investigation. This includes:

- Address and location of the site
- Present owner and current users of the site
- Responsible parties for the assessment and management, if this is not the owner
- List of previous owners and site users
- Chronological list of former industrial or potentially contaminating land use
- Responsible supervisory authority
- Legal basis for operating licence
- Territorial border of the facility and delimitation of area under investigation
- Current site plan with significant environmental features
- Existing monitoring installations

2.2 SITE SETTINGS

The site settings include all relevant features and parameters, characterising the environmental surrounding area of concern:

- **Topography**

The topography as the expression of geological and hydrological conditions characterises the local physiography and use and should be regarded concerning the regional context of the area under investigation.

- **Geology and Hydrogeology**

The regional geology can be obtained from available maps and data bases and, if required, supplemented by geological mapping of selected areas and by subsurface investigations (drillings, geophysical methods, etc.). The geology is especially relevant for the characterisation of local aquifers (depths, location, extent). The geologic conditions affect the release and movement of contaminants (migration pathways). Geological (stratigraphy, geomorphology) and hydrogeological (watershed, groundwater characteristics, existence of hydraulic barriers, springs) data have to be taken into consideration in regard to potential remediation strategies. Furthermore data on natural hazards such as landslides and seismic events have to be taken into consideration.

- Hydrology

Data on surface water, as potential catchment area for contaminants, and data on flow regimes, as potential pathways for contaminated material. Furthermore data on discharge rates including seasonal variations.

- Climate conditions

Meteorological data (long-term means and maximums of annual rainfall and temperatures, wind characteristics, climate zone etc.) and hydrological data (infiltration, evaporation) provide information on potential dispersion of contaminated material (e.g., top runoff events) and on site specific approaches with regard to investigation objectives such as, e.g., remediation.

- Biota

Baseline information on flora and fauna communities of the site and its immediate surroundings. Listing of unique, rare, endangered and vulnerable native species and their significance of occurrence at the site in relation to their overall status, distribution and condition.

- Layout of the site

Identification of possible contamination sources or migration pathways such as mills, ponds, pipelines, infrastructure, drainage systems, location of disposal areas and changes of depositing areas (former tailings ponds).

- Surface condition

Description on the nature of tailings material (fresh, weathered), whether the impoundment is covered by vegetation or water, etc. All these aspects have a crucial effect on the physical stability of the tailings facility and the mobility of contaminants.

- Surrounding land uses

Including population density, contiguous nature protection areas, drinking water intakes, etc. as potential receptor of environmental pollution.

2.3 SITE HISTORY AND GENERAL SITE PARAMETERS

The compilation of a thorough documentation of site history provides valuable information on materials and substances to be expected, on potential hazard areas and on past safety-related events. General parameters comprehend all actual data on minerals or ore processing, tailings treatment, facility design, monitoring etc.

- Historical and current site data

- Composition of bedrock and ore(s), including changes of ore qualities during mine life
- Physical and chemical parameters of tailings material and dams
- Physical and chemical parameters of leachate, drainage water and groundwater

- Data on historical and current methods of minerals or ore processing and tailings deposition

- Processing technique
- Concentrations and quantities of chemicals used in mineral process (if possible, systematic names and also trade names)
- Use of toxic substances
- Ingredient reclamation or treatment processes (e.g. regarding cyanide)
- Water management (flow scheme if applicable)
- Average slurry density and final tailings density
- Changes in minerals or ore processing and treatment of by-products

- Information on historical incidents

- Former spills or dam failures
- Freezing of pipelines
- Characterisation and quantity of the spilled materials
- Effects on environment, public complaints
- Intervention and remediation actions
- Regulatory actions

- General conditions

- Current status of the facility (operating, closed or abandoned) including operation period and the expected mine life-time
- The average rate (metric tons/day) of ore and waste rock mined, ore processed and tailings produced (MINISTERE DES RESSOURCES NATURELLES DU QUEBEC 1997)
- The tonnage and volume of tailings and waste rock placed and to be placed in surface impoundments on accumulation areas until operations are shut down (MINISTERE DES RESSOURCES NATURELLES DU QUEBEC 1997)
- Repairs and rebuildings since commissioning of the facility
- Design of tailings dam (building method, used material, current and approved vertical and horizontal extent, etc.)
- Design and extent of tailings pond (single- or multi-basins, extent and slope of the beach, free-board etc.) including storage capacity available for tailings materials
- Inflow (continuous/discontinuous, punctiform/linear)
- Other inflows to tailings pond
- Frost area in the sediment
- Estimated flood heights
- Spillway design and location
- Existing erosion protections
- Monitoring programs (alarm plan and measures)

3 PHASE 2: DETAILED INVESTIGATION - SITE SPECIFIC APPROACH

The further, more detailed and focused investigation has to consider on one side the overall objective of the investigation, e.g. risk assessments, action plans, improved monitoring, remediation issues, necessary changes in process flows, sustainable closure etc., and the current operating status of the plant, i.e. is it an active facility or a closed respectively abandoned plant. Classification or categorisation of tailings facilities in consideration of the site status and the overall investigation task aspects is the first step towards further investigation (Phase 2a). On the other side the choosing of sampling strategies and analytical methods depends by any means on the extension of the area under investigation, the type and composition of tailings and the expected contaminants (Phase 2b). Therefore an approach specific to operating status, overall task and tailings material has to be chosen, in other words a site specific approach.

4 PHASE 2A: SITE CATEGORISATION IN CONSIDERATION OF THE OVERALL SITE INVESTIGATION OBJECTIVES AND THE SITE'S OPERATING STATUS

4.1 CHARACTERISATION OF ABANDONED SITES

The investigation of an abandoned mine site is in most cases associated with the plan to remediate the site. Some issues that should be taken into consideration concerning the characteristics of abandoned mine sites are:

Size and Location of the Site

Abandoned mine sites may have impacts over large areas especially when nearby watersheds are considered. Often the remote location of these sites, in some cases without direct road access, presents major difficulties.

Structure / Construction of Ponds and Dams

The construction method and the resulting internal structure of ponds and dams strongly influence the physical stability of the facility and the distribution and migration of contaminants.

Volume of Contaminants

Typical of some abandoned mining sites is the very large volumes of mining process waste generated. *"As an example, one tailings impoundment in the now closed Anaconda mine/smelter site near Butte, Montana covers more than 1000 acres and ranges in depth up to 100 feet"* (EPA 2000a). This makes a comprehensive investigation for site characterisation, e.g. with the goal of site remediation, very extensive.

Types of Waste

There may be numerous different types of waste at abandoned mining sites such as tailings, slags, overburden, waste rock and remaining process chemicals. A variety of sampling strategies are necessary to characterise each type of waste.

Persistence of the Contaminants

At abandoned mine sites, primary contaminants are often metals which do not readily decompose or biodegrade into less toxic by-products. Therefore, mine sites abandoned for decades or even centuries can still have metal concentrations at levels of concern, or can for decades release acidity.

Variety of Media Affected

Contamination at abandoned mine sites often concerns different media. Metal leaching can pollute surface water and groundwater. Soil quality is negatively affected by historical waste management practices and by dust and smelter emissions. Sediments of surface water bodies may also contain contaminants. In addition, eroded contaminated particles from tailings facilities may be aerially transported as dust over long distances and thus cause a wide dissemination of contamination.

Initial Levels / Natural Background

The usually long history of mining and mineral processing in abandoned mine areas holds problems in determining the actual natural background levels of substances in local water bodies and soils.

4.2 SITE CHARACTERISATION AS BASIS FOR REMEDIATION PLANNING

A first step and an important aspect for environmental protection in regard to a sustainable site rehabilitation is determining the pre-mining baseline conditions (EPA 2000a, ROBERTSON 1996). Many repercussions of mining operations are time dependent and can take many years or decades, thus, especially in view of remediation efforts, attention should be paid to long-term impacts of parameters

such as erosion processes, chemical condition changes (including secondary mineralisation/degradation and acid drainage) and dam stability properties. The possibilities of simulating in laboratory tests potential long-term effects of short-run sites or of sites with recent changes in operation processes are limited.

A site characterisation as basis for remediation planning has to include data concerning the special objectives of the planned remedial activities. These data are, in addition to the usual data on physical and chemical stability, aspects of future land uses (e.g., tolerable contaminant threshold values) and aesthetic environmental aspects (landscaping).

The initial stages of remediation require the analysis of discharged seepage water for its chemical composition and pH values. Pore pressure measurements within the impoundment indicate the consolidation and hydrologic conditions and prove the effectiveness of the diversion and spillway facilities that have been provided. The frequency of observations and measurements usually becomes progressively less during the remediation phase, depending on the success of the stabilization of the tailings dam and the reduction of danger to the environment (ICOLD 1996b).

4.3 SITE CHARACTERISATION AS BASIS FOR THE ASSESSMENT OF OPERATIONAL RELIABILITY

Monitoring of an active tailings facility requires certain data accuracy, usually defined in the applicable regulations, to discover deficiencies at an early stage. At this, particular attention will be given to loss and emission of seepage water, movement and deformation of impoundments, changes in stress ratio, pore water pressure, measurement of water level, and changes in surface sealing (DIN 19 700 T10).

5 PHASE 2B: CHARACTERISATION OF TAILINGS MATERIAL

An outline of materials and substances commonly associated with the site specific operation processes can be the basis for a first estimation of a potential risk concerning the physical stability of the tailings facility and give initial ideas on potentially appearing contaminants. The characterisation of tailings material, deposited in ponds and used for dam building, includes:

- specifying the types of tailings (conventional, thickened etc.)
- concentrations and behaviour of contaminants (total value, mobilisation potential)
- acid generation or acid neutralisation capacity
- extent of contaminated area (delimitation of the affected zone, dispersion pattern of contaminants concentration)
- geotechnical behaviour of the tailings material (including plasticity, consolidation, shear strength)
- physical stability of tailings dams (this includes also: water level of the open water surface and inside the sediment body, respectively inside the dam)
- behaviour of the dried and weathered tailings material
- erosion resistance

The characterisation of the tailings material is achieved by determination of the following parameters:

- **Mineralogy**

Determination of clay mineral types is important concerning the assessment of physical stability characteristics and sorptive (towards contaminants) properties. Gathering data on secondary mineral growths in the pore spaces of waste materials (by SEM) may give knowledge that can be used

to refine models of contaminants fate and transport, by clarifying the potential for sorption onto the surfaces of clays or other minerals.

- **Chemical composition**

Identifying types and concentrations of contaminants and acid generation potential.

- **Particle-size characteristics**

Grain size of tailings will affect hydraulic conductivity, radon exhalation, wind-blown dust and chemical reactions (RITCEY 1989). Also the stability of the tailings dam is largely controlled by the grain size distribution. The potential of tailings materials to generate acidity or to release contaminants to the environment by leaching depends also partly on the particle size characteristics. Particle-size affects reaction rates and reaction duration due to the extent of specific surface, the distances between reactive particles and the permeability of the tailings material. Particle size grading potentially offers preferred pathways for the flow of water through the material.

- **Physical features**

Important material properties in view of assessing the tailings facilities stability are bulk density, plasticity, consolidation, shear strength, water content, water permeability and last but not least the amount and type of clay minerals with different sorptive qualities. Most of these features will also influence settlement, erosion sensitivity, oxygen penetration (important concerning pyrite oxidation) and radon exhalation.

5.1 PROCESSES GOVERNING THE CHARACTERISTICS AND THE BEHAVIOUR OF TAILINGS MATERIAL

Weathering processes, also occurring in depth (STANTON 2000), affect the character of tailings in many different ways and change chemical and physical properties of the material. These processes may cause decomposition, secondary mineral growth, the development of new pathways for hazardous substances, metal mobilisation, and the dispersion of eroded, contaminated surface material. Also changes in mining, processing, and disposal methods or variations in the geology of the ore or gangue materials may cause potential variations in the tailings characteristics. Tab. 1 shows effects of mineral processing steps on tailings characteristics.

The characteristics of tailings is, beside local conditions of the site, the most important fact that influences the behaviour of tailings material in ponds/dams and therefore controls directly the safety of tailings facilities and their potential environmental risk (Tab. 2 and 3).

Some typical characteristics of tailings result from special ore processing practices (DEPARTMENT OF NATURAL RESOURCES & ENVIRONMENT 2002¹, RITCEY 1989², VICK 1983³):

- Base metal (Cd, Cu, Pb, Ni, Sn, Zn) tailings are generally fine grained with a significant clay content, and have a high acid generating potential.¹⁾
- Gold tailings have been subjected to a cyanidation process, and may be acid generating.¹⁾
- Uranium tailings are radioactive and contain a high percentage of chemical precipitates (gypsum and metal hydroxides).¹⁾
- Coal tailings usually have two components, a coarse reject and washery fines, both of which are sometimes acid generating when pyrite is present.¹⁾
- Nickel Tailings have been subjected to high temperature and pressure leaching, followed by neutralisation, that influence the material properties.¹⁾

- Alumina Red Mud tailings have a high alkalinity.¹⁾
- Iron tailings are dominated by the minerals quartz, hematite, goethite, mica, chlorite and clay and constitute an environmental problem in the release of “red water”.²⁾
- Phosphate tailings consist of a clay-slime slurry with only 5% solids and, caused by the slow settling, require a large impounding area.²⁾
- Potash tailings comprise a coarse, sandy fraction containing a large portion of salt (with the sensitivity to liquefaction) and a clay fraction (with slow sedimentation characteristics).³⁾

Tab. 2: Effects of mineral processing steps on tailings characteristics (EUROPEAN COMMISSION 2003 - BAT).

Process step	grain size distribution	generation of fines	specific surface	% sol-ids	reagents	pH	ARD influence	surface properties	particle shape
comminution	X	X ¹⁾	X	X ²⁾	-	-	X	X	X
screening	X	X ³⁾	-	-	-	-	-	-	-
classification	X	X	-	X	-	-	X	-	-
gravity conc.	-	-	-	X	-	-	X	-	-
flotation	-	-	-	X ⁴⁾	X ⁵⁾	X ⁶⁾	X	X	-
magnetic sep.	-	-	-	-	- ⁷⁾	-	X	-	-
electric sep.	-	-	-	-	X	-	X	X	-
sorting	-	-	-	-	-	-	X	-	-
leaching	-	-	-	X	X	X	-	X	-
thickening	-	-	-	X ⁸⁾	X ⁹⁾	-	-	X	-
filtering	-	-	-	X	X	X ¹⁰⁾	-	X	-

¹⁾ e.g. agitated mill generates more fines than ball mill
²⁾ crushing dry, tumbling mills and agitated mills wet process
³⁾ excessive screening can lead to generation of fines
⁴⁾ flotation is always a wet process with about 30-40 % sol., in most cases water will have to be added
⁵⁾ see 2.3.2 for details
⁶⁾ raised or lowered
⁷⁾ usually no reagents, however for fines sometimes dispersion agents are used for deagglomeration
⁸⁾ obviously % solids are reduced by thickening
⁹⁾ often use of flocculants (see 2.3.2 for details)
¹⁰⁾ e.g. by using flocculants such as aluminium sulphate or lime, which change pH

With regard to the tailings characteristics the types of tailings can be divided into four categories (VICK 1983):

- Soft-rock tailings (such as from potash processing) contain sand and slime fraction with the presence of clay; the slime fraction dominates the properties.
- Hard-rock tailings (such as from base metal and gold processing) contain sand and slime fraction with low plasticity; the sand fraction controls the engineering properties.

- Fine tailings (such as from red muds)
characteristics are dominated by silt- or clay-sized particles.
- Coarse tailings (such as from uranium processing)
contain either sands or non-plastic silt particles with sand-like behaviour.

Tab. 3: The correlation between tailings characteristics and tailings behaviour (EUROPEAN COMMISSION 2003 - BAT).

Tailings behaviour	Tailings characteristics								
	grain size distribution	finer	specific surface	% solids	reagents	pH	ARD influence	surface properties	particle shape
Permeability	X	X	X	-	-	-	-	X	X
Plasticity	X	X	X	-	-	-	-	-	X
Shear strength	X	X	X	-	-	-	-	X	X
Compressibility	X	X	X	-	-	-	-	X	X
Tendency to liquefaction	X	X	X	X	-	-	-	X	X
Chemical properties	-	X ¹	X ¹	- X	X	X	X	X	
Density (in- place and relative)	X	X	X	-	-	-	-	X	X
Consolidation	X	X	X	-	-	-	-	X	X
dusting	X	X	-	X	-	-	-	-	-
Toxicity of discharge	X ²	-	X ²	-	X	X	X	X	-
Tailings delivery	X	X	-	X	-	-	X	-	-
Deposition	X	X	-	X	-	-	X	-	-
Free water management	X	X	-	X	X	X	X	-	-
Seepage flow	X	X	X	X	-	-	-	X	X
Long-term safety	X	X	X	-	-	-	-	X	X
ARD management	X	X	X	-	-	X	X	X	-
Emissions to air	X	X	-	X	-	-	-	-	-
Emissions to water	X	X	-	X	X	X	X	X	-
Emissions to land	X	X	-	X	X	-	X	-	-
Effluent treatment	X	X	X	X	X	X	X	X	X
Dam construction	X	X	X	X	X	X	X	X	X
Monitoring	-	X	-	-	X	X	X	-	-
Closure and after-care	X	X	X	X	X	X	X	X	X

¹⁾ because of increased/alterd availability
²⁾ if ARD producing tailings and exposed to the atmosphere

5.2 APPROACH TO SAMPLING AND ANALYSIS

The preliminary step in regard to setting up a sampling and analysis plan must be the definition of the required data quality in respect of the overall objectives of the project. In this connexion it must be distinguished between “screening data” and “definitive data”. In cases where historical site information is not available, screening data are useful to give a first overview of the present status, as basis of an appropriate sampling strategy, and therefore help reducing the initial sampling and analytics costs. Screening data are based on spot tests, with simpler sample preparation and rapid, less precise analytical methods, partly based on in situ methods. Definitive data are achieved by using an exact sampling grid and strict analytical methods to allow a comprehensive and reliable site characterisation with a sound description of the vertical and horizontal distribution of the analysed parameters.

After defining the data quality, a sampling and analysis strategy should be developed, taking into account the extension of the area under investigation, the type and composition of tailings, the parameters to be analysed, and, when considering chemical parameters, the potential migration pathways of contaminants from the source. At this point, it can also be very beneficial to talk to the staff on the location for getting knowledge on former disposal areas, transportation ways, design of older tailings dams or general changes in the processing methods. An understanding of the processing operations taking place or have taken place on the site in the past simplifies the defining of an adequate sampling approach and may save time and costs. A sampling and analysis plan ensures the consistency of sampling and data collection practices and activities over time. However this schedule is not intended to be something statically but should be adjusted if necessary after receiving new data. The aim of the sampling and analysis plan is collecting defensible data of known quality, appropriate for the investigation objectives.

In this paper there are only information provided on collection techniques for soils. Other media, although they may be necessary to be included as part of a detailed site investigation, are not considered due to the fact that they can be sampled following standard procedures.

In order to minimise the uncertainty, the soil sampling should be based on a conceptual site model, a thorough understanding of the site conditions and the site history, and the consideration of former investigation data (e.g. remote sensing, geophysics). A sampling and analysis plan should be set up before any field work begins and should comprise three parts:

- **Data quality assurance principles**, describing the proceedings and activities necessary for achieving data quality objectives and hold out against legal and scientific scrutiny.
- **Field sampling plan**, which defines the sampling and data collection methods to be used for all field work, such as types of samples, number of samples, depth of samples, pattern of samples locations (grid based and/or judgemental), and the way of onsite data recording. Beside this also the type of sample container (glass, plastic), the maximum duration of storage and the environment in which samples will be stored (e.g., lightproof storage, cooled) prior to analysis have to be decided on.
- **Analyses line-up**, a compilation of all types of field analyses and laboratory analysis methods.

5.3 DATA QUALITY ASSURANCE

Data quality objectives are ensured by the representativeness and integrity of samples and the reliability of the analytical proceedings. This includes adequate sample preservation and minimisation of sample contamination in the field, to avoid falsification of analytical results. In the laboratory proper handling and storage of the samples and an accurate analytical approach is indispensable. Generally, at any step the transfer of data as source of errors should be carefully attended.

5.4 SAMPLING METHODS

Before undertaking the actual work on site (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003):

- The potential health hazard at the site for the sampling team should be assessed and precautions taken.
- The necessary permits from the responsible authority for undertaking the work must be obtained, as well as the permission to access the site and the individual sampling locations.
- Ensure the availability of suitably trained and qualified site personnel.

The selected sampling locations should include all relevant points as defined in the field sampling plan, including contaminant sources, contaminant migration pathways, and habitats of concern in the vicinity. The heterogeneity of the area under investigation has to be taken into account, e.g. the weathered surface, potential salt crusts, hardpan ledges, and the uneven distribution of grain sizes. Alteration of chemical and mineralogical zoning may have a significant impact on, e.g., pH and on resultant release of contaminants. Using three-dimensional geostatistical techniques (EPA 2003), similar to those used to characterise the ore body, these variability can be evaluated. Fixing the number of sampling locations and number of samples, a compromise must be found concerning the total number of samples and consequent amount of analysis (large number of samples means improved quality of data) on one hand versus the required time and expense (costs) on the other hand. Re-sampling of a site (following the same sampling strategy than before) may lead to different results for the mean analytical values of the samples, but if the sampling density and pattern is identical the general site characterisation outcome has to be the same. The more heterogeneous an area is, the more samples are needed to provide a representative characterisation. According to EPA 2003 "... *representativeness expresses the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, or a process or environmental condition.*" Also visual effects can provide useful information, such as visible sulfides, stainings, disturbed or distressed biota.

The characterisation of a tailings impoundment will require the collection of samples laterally and vertically throughout the deposit. Data gathered from these samples can be used to draw a three-dimensional image of the volume, the chemical character and physical conditions of the disposal. The actual sampling should take place during periods when environmental conditions favour the concentration of chemicals in environmental media (spring/fall when flushing by infiltration is normally greatest), when staining may be most apparent (mid-summer) and when hot spots can be easily observed (after snowfall) (ROBERTSON 1996).

Sampling patterns

- Randomly gridded sampling:
ensures that any sampling location within a sampling area has an equal chance of being selected as a sampling point and may be used to collect screening data for a first estimation of a unknown site, but is deficient for detecting hotspots or giving an overall picture of the contamination distribution.
- Judgemental selected sampling:
data of sampling points, selected on the basis of experience or knowledge of the site, may be used for preliminary assessment of known contaminated areas (identified from reliable information on the site), for particular features in monitoring sampling (e.g. post remediation) or for information what chemicals may be present. But the usefulness of the data for statistical interpretation is limited.
- Systematic grid based sampling:
sampling points are selected at regular and even intervals and can be used in the case of an inadequate documentation of the site history or to complete a random sampling, and provides the most comprehensive data basis for site characterisation.

- Stratified sampling:
used for large and complex sites and divides them into non-overlapping sub-areas with different sampling patterns.

Sampling density

Mathematical formulae for determining sampling density are usually based on two conditions: 1. the results have to be normally distributed, and 2. a particular concentration is equally likely to occur at any point. This requires knowledge on average results and the standard deviation of the results, which can be rarely achieved during initial investigation, especially in case of heterogeneous sites. So sampling must be regarded as a screening process with the aim to reduce the likelihood of a false negative result (NATIONAL ENVIRONMENT PROTECTION COUNCIL 1999).

Coming to the right decision concerning the sampling density is mostly based on the quality of the available historical site information and the representativeness of the attained screening data. The site specific amount of samples will depend on various factors, such as current and proposed use of the site, expected distribution of contamination and of "hot spots", purpose of sampling (detection of the mean concentration of a parameter, detection of hot spots or identification of contaminated land), presence of groundwater, and size of the site.

A method using a systematic sampling pattern for calculating the minimum number of sample locations to detect the diameter of circular hot spots with 95% confidence is provided in "Contaminated Land Management, Guideline No. 5, Appendix E" (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003).

Sample quantity

The number of samples is sufficient, when additional sampling would not yield information that could change the result.

Sample depth

The same facts that influence the decision on the sampling density are relevant for determining the sampling depth. Soil samples must be collected at more than one depth to establish the vertical extent of contamination. Special attention should be given to the potential mobility of detected contaminants, the depth of groundwater table and the proposed use of the site.

Samples of varying depths provide data for different questions. Surface samples may represent fresh, contaminated material, contamination from airborne dust or spills. Samples taken from greater depth may represent contaminants being in contact with the soil for long time or unstressed material to be used for background data. Contaminants available for plant uptake must be sampled at defined depth taking into account the vegetation of concern. Samples taken from different depths may represent spatial changes in the tailings disposal.

Sampling techniques

Samples must be obtained in a manner that retains the sample integrity. Following techniques may be considered (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003):

- Surface and shallow subsurface grab sampling (typically 75-100 mm depths)
Advantage: Low cost, quick, no access restrictions, minimal soil disturbance.
Disadvantage: Impractical in difficult soil conditions, care required to ensure quality of sample recovered.
- Hand auger or tube sampling (depending on soil type depths of to 2-3 m can be achieved)
Advantage: Low cost, quick, no access restrictions, minimal soil disturbance.

- Disadvantage: Impractical in difficult soil conditions, care required to ensure quality of sample recovered, limited ability to observe nature of material, labour-intensive.
- Borehole sampling (extend up to 10 m or greater depths)
 - Advantage: Minor disturbance of soils, limited occupational exposure, accurate recovery of samples, ability to sample at depth, suitable for most ground conditions.
 - Disadvantage: More expensive than other techniques, limited ability to observe materials, can cause preferential pathways for contaminant migration if not appropriately constructed, depending on the size of the equipment access to the site may be limited.

Sample types

can be classified in undisturbed or disturbed samples and discrete (spot) or composite sample:

- Undisturbed or disturbed samples:
 - depending on the intended analytic method.
- Discrete (spot) sample:
 - are samples collected over a discrete representative sampling interval (EGIS 2001).
- Composite sample

Composite sampling are mixed equal quantities of individually collected samples (sub-samples) from different locations. The analytical results of such composite samples represent the average of the constituent sub-samples. Composite sampling reduces the number of samples to be analysed and consequently the analytical costs. Sample compositing must be used carefully as high contaminant concentrations in one or more of the sub-samples can be masked by the dilution effect of the other sub-samples (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003).

On a workshop 1997 in Denver (U.S. Geological Survey, Mineral Resource Program Solid-Phase Sampling workshop) participants developed a statistical mine-waste dump sampling strategy for abandoned mine sites, a tool for a rapid screening based on composite samples from individual dumps. According to the authors "*one 30-increment dump-composite sample ... contains as much information, relative to average value, as 30 individual grab samples at 1/30 of the analytical costs.*" For minimising sampling errors a mixed sample should consist of at least 30 sub-samples, this means, dividing the mine dump into at least 30 cells of roughly equal surface area and collecting samples of roughly equal mass from each cell (SMITH et al. 2000a).

On this the U.S. Environmental Protection Agency (EPA 2000b) states that "*composite samples reflect a physical rather than a mathematical mechanism for averaging. Therefore, compositing should be generally avoided if population parameters other than a mean are of interests...*" That means, compositing is only acceptable when average properties are of interest. "*Composite sampling is often incompatible with health risk assessment and is generally unsuitable for definitive assessment of site contamination due to the inherent uncertainties in the resultant data.*" (LOCK 1996, in NATIONAL ENVIRONMENT PROTECTION COUNCIL 1999).

According to the MINISTRY FOR THE ENVIRONMENT NEW ZEALAND (2003), some principles that have to be taken into account for composite sampling are:

- Hotspots or broad scale contamination have to be known, e.g. by a comprehensive site history evaluation.
- All composite samples have to be made up of the same number of equally sized sub-samples.
- No more than four sub-samples should be used to make up the composite, although the number is governed by the analytical detection limits.
- Sub-samples are usually taken from adjacent locations and from similar depths.

- Mixing of the sub-samples must be undertaken in the laboratory and original samples retained for possible retesting.
- Composite sampling is not suitable for soils that are not easily mixed (e.g., clays).
- When comparing composite results against guideline values, the guideline value must be adjusted by dividing the value by the number of sub-samples in the composite.

Background samples

Background samples are used as a reference point for interpreting and classifying the attained site data in view of the local conditions (i.e. are contaminants occurring at the site of natural or artificial origin) and legal guidelines (threshold values).

The location for background sampling should normally be upwind/upstream of the site and must represent the characteristics of the undisturbed site. For these purposes also an unaffected watershed in the surrounding area of the site can be used for background water samples. Whereas at least one background sample should be collected, the heterogeneous nature of tailings sites may however necessitate to collect more than one set of background data. Information on background levels may possibly be also requested from regional councils or site owners.

Sample handling

- Sample logging

The log (field notebook) must include identification of the site, general observations regarding sampling locations, depth of samples, weather conditions, ground surface conditions and any observations or measurements, which could influence the interpretation of the results. The sampling records should be dated and signed. Photography of the sampling location and procedure might supplement the documentation.

- Sample labels

Sample labeling must include: unique sample reference number, exact location of sampling, sample type (potential analyses to be performed), collection date and time, sample preservation method, and name of the staff who took the sample.

5.6 ANALYTICAL METHODS

Geochemical and mineralogical analysis provides information on the potential of the tailings material to release metals or other toxic contaminants and on its potential for acid generation. Results of geotechnical tests in general permit estimation of potential risks of the tailings plant stability. Due to the fact that laboratory methods are conducted with the intention to speed up natural processes, test results must be interpreted with caution especially in regard to the long-term behaviour of the material. In any case, the choice of the adequate analytical method is directly governed by the kind of tailings material to be investigated.

According to MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND (2003) the laboratory should be able to provide a validation report for any methods used, which must include specificity for the compounds being analysed, analytical range, recovery efficiency from the matrix, method detection limit and precision within batch and between batches.

The following compilation of methods, test procedures and approaches should not be seen as exhaustive, but as an overview of the most common methodology.

5.6.1 GEOCHEMICAL AND MINERALOGICAL ANALYSIS

Mineralogy

Most methods require the dissolution of the solid material before analysis. An exception is X-Ray Diffraction (XRD) and Thermal Analysis (TA) used to identify mineral phases and to determine the major and minor chemical constituents in soil samples.

Weathered mine waste material, however, often contains a significant portion (40-50%) of amorphous or poorly crystalline material and therefore it is necessary to combine XRD with other methods that can address the amorphous phases (SMITH et al. 2000b).

Trace elements

Scanning Electron Microscopy (SEM) locates microscopic phases and particles containing trace elements, which can be individually analysed to determine mineral chemistry, mineral identification, weathering sequences, reaction products and grain coatings.

Organic carbon

TOC (total organic carbon) analysis by means of high-temperature oxidation (1050°C). Using a catalyst, the carbon is oxidised to CO₂ and can be determined via a NDIR (non-dispersive infrared) detector. The TOC content results from the difference of the measured TC (total carbon) and TIC (total inorganic carbon) values.

Carbonate content

After acidification the carbonate content can be determined through volumetric gas analysis using a so-called calcimeter (method after SCHEIBLER).

Loss on ignition

Detecting the weight loss of a material, usually expressed as percent of the original dry weight, after burning at selected temperatures (550°C according to DIN 19684-3, in LFU-LFW 2002).

Sulfur/Sulfide/Sulfate contents

In view of the different potentials for acid production of the varying forms of sulfur occurring in metal mining wastes (LAPAKKO 2002), it seems to be indispensable for an adequate tailings characteristic to choose an analytical method which allows to specify the various sulfur forms.

Different sulfur species are often determined by treating the sample to remove a specific sulfur phase, and using a determination of total sulfur on the original and treated sample to determine the change in sulfur content resulting from the extraction (LAPAKKO 2002).

An overview and assessment of ASTM (American Society for Testing and Materials) methods for determining total sulfur and on several other analytical methods for determining various sulfur species is given in "Metal Mine Rock and Waste - Characterization Tools: An Overview" (LAPAKKO 2002).

Another code of practice for determining inorganic sulfur species (sulfide sulfur, disulfide sulfur, soluble sulfate sulfur) and organic sulfur is the method following DIN 51724 T1+T2.

Heavy metal content

The determination of the acid soluble metal fraction can be carried out according to the chemical pulping by acid digestion given in e.g. DIN 38 414-H7. Another common method is the acid digestion in a microwave system.

The potential of heavy metal release to the environment not only results in consequence of the concentration, but also depends on the way the heavy metals are fixed in the tailings matrix (solid speciation). The speciation of metals can be analysed by sequential chemical extractions.

In a sequence of chemical extractions, metals are extracted from some or all of the defined phases (e.g., water-soluble, ion-exchangeable, carbonate, amorphous Fe-oxide, crystalline Fe-oxide, organics, sulfide, silicate). The increasing chemical strength of the extraction solutions provides a basis for evaluating the potential of the metals for mobilisation. A detailed description of the methods, a discussion of the mineralogical and particle size effects on the results, as well as an estimation of metal mobilities is given in LEINZ et al. (2000).

Cation exchange capacity

A number of protocols for the determination of the cation exchange capacity (CEC) exists. The Silver-thiourea method after CHHABRA et al. (1975) has the advantage of being a one-step-method and therefore being time- and cost-effective.

Acid generating potential

There are a variety of test methods to determine the potential of tailings materials to produce acid. An important point of choosing the adequate method is, especially in regard to historical mining waste with weathered surfaces, that the used method should also take into account the potential acid production of secondary and tertiary minerals and the potential acid-consuming capacity of host-rock minerals (e.g., carbonates, chlorite, biotite).

Two approaches to analyse the potential of tailings material for acid production can be distinguished: 1. static test methods, and 2. kinetic tests.

Static test methods

Static predictive tests are quick and comparatively inexpensive, but provide no information on the quality of effluent that may drain from tailings materials in the future (EPA 2003). Nevertheless, these tests can be used as a screening tool and provide information on further necessary investigations. The most common static test is the Acid Base Accounting (ABA) and several variations and modifications of it. The ABA measures the balance between the acid-producing potential (AP) and the acid neutralizing potential (NP). AP is determined by a sulfur assay and represents the sulfur contained in acid-generating iron-sulfide minerals present in the sample. NP is determined by subjecting the mine-waste sample to some form of acid digestion and represents the amount of acid-neutralizing carbonate minerals present in the sample. The net-neutralizing potential (NNP), which is the difference between these values ($NP - AP = NNP$), is one of the measurements used to classify a mine-waste sample as potentially acid or non-acid producing (WHITE et al.1999).

The Net Acid Production (NAP) and Net Acid Generation (NAG) methods are based on the principle that hydrogen peroxide accelerates the oxidation of iron sulfide minerals. The acid consequently produced dissolves neutralizing minerals present, and the net result of the acid production and neutralization can be measured directly. This test does not require sulfur determination and is, therefore, more readily conducted in a field laboratory than other static tests (WHITE et al.1999).

A compilation of several common methods, further information on the differences of the varying procedures including the advantages/disadvantages of them, and an overview which parameters (such as particle size of the sample, amount/type of acid added, back titration endpoint, temperature) affect the NP-results are given in "Static-Test Methods most commonly used to predict Acid Mine Drainage: Practical Guidelines for Use and Interpretation" (WHITE et al.1999).

Kinetic test methods

To define reaction rates through time, kinetic tests simulate the specific environmental conditions by accelerating the natural weathering rate of a mine waste sample under closely controlled laboratory conditions. They are long-term tests (weeks, months and sometimes years) and significantly more expensive than static tests. But kinetic tests have to be used to confirm or reduce uncertainty in static-test classifications (i.e., the sample is either acid- or non-acid producing), to identify dominant

chemical-weathering reactions, to determine acid-generation rates and to estimate the quality of resulting drainage.

The most common laboratory kinetic test methods for determining acid drainage characteristics are based on humidity cells, columns or lysimeters. The procedures of the different kinetic tests are similar to one another and include that a sample is subjected to periodic leaching, with the leachate being collected and analysed as basis for identifying the rates of acid generation, metals release and neutralization capacity depletion. The tests differ in the sample preparation, the test conditions (lab/field), and the test duration.

A compilation and detailed description of these and other kinetic test methods, including some remarks on result interpretation, is given in "A Source Book for Industry in the Northwest and Alaska. - Appendix C: Characterization of Ore, Waste Rock, and Tailings" (EPA 2003).

In general, the approach of an acid mine drainage testing is divided in a two-step program in which first static tests of numerous samples are carried out to identify potentially acid-generating units and to characterise the variability that occurs within them. In the second step, kinetic tests will be carried out on samples representative of the range of compositions within potentially reactive units to determine whether acid drainage will occur (EPA 2003).

Other methods

A common and simple field test is the paste pH method which can be used to assess the presence of soluble acid salts in tailings. Most methods use a 1:1 weight ratio of distilled water to air dried solids, but sample mass and equilibration time of the water-solids mixture prior to pH measurement may vary among methods (LAPAKKO 2002).

Slightly more labour-intensive is the Acid Concentration Present (ACP) test, but it supplies an estimate of acidity present rather than simply pH. The initial pH of a mixture of air dried sample material and deionised water is recorded and then titrated to pH 7 with NaOH (LAPAKKO 2002).

Leaching tests

Metals or other contaminants can be leached from tailings materials even under different conditions (neutral conditions or by acid generation). Consequently, a variety of leaching tests are used to determine the potential for contaminants to mobilise from the soil phase to the water phase under the expected environmental conditions. A leaching test is an extraction procedure in which soil contaminants are extracted into a liquid phase. The resultant extract, the leachate, can then be analysed for the parameters of interest.

In general there are two different methods of leaching tests: extraction test (with a single defined volume of leaching fluid) and dynamic extraction tests (with continuously or intermittently renewed leaching fluid during the test). Another major difference is the choice of the leaching medium, e.g. acid or deionised water. The "Draft Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities" (EUROPEAN COMMISSION 2003) states that "*Extraction tests using deionised water as the leaching medium, such as DIN 38414-S4, modified SWEP etc. more closely approximate conditions in a tailings and waste-rock management facility*".

Some leaching test methods used for regulatory purpose (specified and compared in EUROPEAN COMMISSION 2003 - BAT) are:

- US EPA Toxicity Characteristic Leaching Procedure (TCLP, Method 1311) - leaching medium: acetic acid - extraction test;
- British Columbia Special Waste Extraction Procedure, SWEP (MELP, 1992) - leaching medium: acetic acid - extraction test;
- British Columbia Special Waste Extraction Procedure, Modified SWEP (MELP, 1992) - leaching medium: de-ionised water - extraction test;

- German standard DIN 38414-S4 - leaching medium: de-ionised water - extraction test;
- French standard AFNOR X 31-210 - leaching medium: de-ionised water - extraction test;
- European Standard EN 12457/1-4 - leaching medium: de-ionised water - extraction test;
- Swiss TVA Eluate test - leaching medium: de-ionised water - dynamic extraction test.

A comparison concerning leaching tests such as US EPA procedures (including the EPA-Method 1312-SPLP - Synthetic Precipitation Leaching Procedure) and further information on other leaching methods is given in "A Source Book for Industry in the Northwest and Alaska. - Appendix C: Characterization of Ore, Waste Rock, and Tailings" (EPA 2003).

Field Leach Test

A quick, qualitative in-situ measurement test for geochemical screening on weathered surfaces is the Field Leach Test described by HAGEMAN and BRIGGS (2000), which is based on the premise that the majority of the chemical reactive potential are very soluble components in the fine fraction (< 2 mm). Only pH and conductivity are in fact measured in-situ, while filtered samples are being prepared for the laboratory determination of other chemical parameters. After SMITH et al. (2000b), the results are tending to slightly overestimate the leachability, but HAGEMAN and BRIGGS (2000) show that the results of the geochemical trends correlate well with the EPA-Method 1312-SPLP.

5.6.2 GEOTECHNICAL ANALYSIS

Water absorption

The ability of an air-dried soil sample to absorb and retain water; method after NEFF.

Water content

The water mass of a soil sample vaporised at 105°C related to the oven-dry soil sample mass. Methods according to DIN ISO 114665 (in LFU-LFW 2002) or DIN 18121 T1.

Grain size distribution

The grain size distribution is determined through wet or dry sieve analysis for materials > 0,125 mm or, for fine materials < 0,125 mm, by methods based on particle settling velocities (method after CASAGRANDE).

Particle density

The oven-dry solid substance mass per volume is determined by, e.g., using a capillary pycnometer after DIN 18124.

Plasticity

Determination of the ATTERBERG consistency limits, as there are liquid limit, plastic limit, e.g. after DIN 18122 T1+T2.

Water permeability

Assessment of the water permeability (= hydraulic conductivity) from the grain size distribution using the empirical relationships set up by, e.g., BAYER and HAZEN (KASENOW 2003). Direct determination can be achieved by column tests, e.g. following the procedures described in DIN 18130 T1.

Shear strength

There are several testing methods for determining different shear parameters. The methods (simple, direct, triaxial or ring shear test) and test conditions (i.e. consolidated or not consolidated, drained or not drained, forced shear plane or free formation of shearing area) that have to be chosen, depend on the required shear parameters for the respective task. Test methods can be realised e.g. according to DIN 18137.

Compactibility

A benchmark for the assessment of achieved or attainable compaction is the proctor-density, in consideration of the water content, resulting from the Proctor-test. Test condition are defined in, e.g., DIN 18127 and ASTM D698 (2000).

Other test methods and further information concerning the listed geotechnical parameters, as well as more possible tests are given in "Draft Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities " (EUROPEAN COMMISSION 2003) and in "Tailings Dams and Seismicity - Review and Recommendation" (ICOLD 1995).

5.7 NON-INVASIVE INVESTIGATION TECHNIQUES

The most common non invasive investigation methods for contamination surveys are geophysical techniques, such as direct current resistivity (DC), electromagnetic (EM), ground-penetrating radar (GPR), seismic refraction, and magnetometry. The selection of the appropriate geophysical technique depends on the site conditions and the investigations objectives. A geophysical survey identifies anomaly locations, i.e. an area where is a contrast with the background measurements. Commonly, the geophysical survey is used to complete initial screening data which can then be investigated by invasive techniques. In addition some techniques can be used to fill data gaps between boreholes or sampling locations or to provide information from inaccessible locations. Calibration of results by comparison with laboratory data is essential.

Remote sensing methods (imaging spectrometers)

SWAYZE et al. (2000a+b, in SMITH et al. 2000b+c) have demonstrated that, based on identifying iron-bearing secondary minerals, airborne or orbital imaging spectrometers can be used to map minerals resulting from weathering of acidic mine waste (best indicator mineral: jarosite) and therefore represent a feasible tool to screen large areas for potentially acidic mine-waste material.

Geophysical methods (airborne geophysical and surface geophysical techniques)

Airborne surveying tools include radiometric, magnetic, and electromagnetic mapping and can be used to map subsurface lithology, structure, and hydrogeological information. The main use in tailing site investigations is to provide information on the surrounding geology, areas of groundwater with high salinity (e.g. plumes) or large inhomogeneities in deposited materials (SMITH et al. 2000b+c). The horizontal and vertical resolution is limited, most methods are expensive. Expert knowledge is necessary for design, conducting and interpretation of airborne geophysical surveys. Thus the use is restricted to large scale investigations where a fast overview is needed to select areas for detailed investigations. Surface geophysical methods comprehend data of direct current resistivity (DC), induced polarisation and spectral induced polarisation (IP, SIP), electromagnetic (EM), seismics and ground-penetrating radar (GPR) and can be used to study conditions at depth, by reflecting structure, lithology, depth to groundwater, and pore water saturation of the tailings area under investigation. DC, IP and EM provide information about mineralogical parameters (especially sulphide minerals) and the location of groundwater or pore water containing high total-dissolved solids (SMITH et al. 2000b+c). In the case of pore water pH < 5, conductivity maps can indicate acid generating potential (CAMPBELL et al. 2000). Seismics and GPR are mainly useful to provide structural investigations. For interpretation of the obtained data expert knowledge is essential. An overview on different geophysical methods and their use for tailings site investigations is given in Table 4.

Tab. 4: Potential uses of geophysical methods in mine-waste characterization (SMITH et al. 2000c).

Method	Measures	Caused By	Mine-Waste Applications
EM (Frequency-Domain Electromagnetics)	Electrical conductivity(mS/m)	Ground water, lithology	Tracing AMD plumes
DC (Direct-Current Resistivity)	Electrical resistivity(Ohm-m)	Ground water, lithology	Shallow (<10 m) water tables in, and bottoms of, shallow (<20 m) waste dumps
TEM (Time-Domain Electromagnetics)	Electrical conductivity(mS/m)	Ground water, lithology	Deeper (10-30 m) water tables in waste dumps
CSAMT (Controlled-Source Audio Magnetotellurics)	Electrical resistivity(Ohm-m)	Ground water, lithology	Deeper (10-50 m) bottoms of waste dumps
IP (Induced Polarization)	Electrical chargeability(usually mV-sec/V)	Electrochemical reactions at grain surfaces	Concentrations of sulfides in waste dumps
SP (Spontaneous Polarization)	Ground voltages(mV)	Redox and streaming potentials	Experimental (no proven successes)
GPR (Ground-Penetrating Radar)	Speed of electromagnetic radiation(cm/ns)	Ground textures and included pore water	Possibly monitoring plume remediation
Magnetics	Magnetic field (nT)	Magnetization	Ferrous junk (e.g., rebar) in mine dumps (other mine-waste applications unproven)
Seismic	Acoustic wave velocity(m/s)	Compaction and ground water content	Tracing bottoms and edges of waste dumps, and basement under plume areas (all mine-waste applications are still in experimental stages)

A literature and case study concerning the feasibility of remote sensing and GIS (geographic information system) techniques for tailings detection was made by SOL et al. (1999). The study includes a listing of spectral and spatial resolution of some easily obtainable satellite images. At the moment, MOS (Modular Optoelectronic Scanner on the Indian remote sensing satellite IRS-P3), appears to be the most suitable instrument for this, but after the successful launch of the European Satellite ENVISAT, the MERIS (Medium Resolution Imaging Spectrometer) instrument will become also very interesting (resolution of 300 m). Furthermore the fields of application for optical remote sensing and radar remote sensing is shown. After SOL et al. (1999), optical remote sensing features a number of advantages for the assessment of mine wastes and tailings:

- the period between image acquisition and the processed result may be relatively short;
- the images are digital, the processing software is usually user friendly;
- if conditions are good, images from different times per year can be available which ensures both seasonal coverage and continuity;
- the images are geographically consistent, determinations at relatively exact locations is possible;
- areas that are not accessible for field surveys can be integrally mapped;

- if the spectral resolution is sufficient and adequate, then discrimination of desired types of objects such as wastes, tailings, contaminated streams, affected areas is possible;
- changes in time can be monitored.

But there are also some restrictions, such as:

- for regular use, high resolution remote sensing is relatively expensive, both in terms of image acquisition and in terms of hardware and software required;
- the interpretation of remote sensing images requires expert knowledge, automation of the entire processing and interpretation procedure is not yet feasible.

5.8 DATA REPORTING

The laboratory report should include the following information for each sample:

- sample identity;
- result for each analyse, including specific definition and appropriate units;
- description of the test method used, including any extraction/digestion procedure, accreditation status of the method, method detection limit.

5.9 DATA VERIFICATION

Some definitions on accuracy and precision of data (MCLEMORE 2002):

Precision: The degree of agreement among repeated measurements of the same parameter. It may be determined by calculating the standard deviation or the coefficient of variance among samples taken from the same place at the same time.

Accuracy: Indicates how close the results are to a true or expected value and can be determined by comparing the analysis of a standard or reference sample to its actual (known) value.

Completeness: The comparison between the amount of valid, or usable, data originally planned to collect, versus how much is collected.

Comparability: The extent to which data can be compared between sample locations or periods of time within a project, or between projects.

5.10 ERRORS

5.10.1 SOURCES OF ERROR

Interpretation

Potential effects of modified in situ conditions for laboratory tests:

- Hydroxide coatings on calcite or sulfate coatings on pyrite may preclude these minerals from participating in acid neutralization or generation.
- Crushing samples to small particle sizes prior to Acid Base Accounting Tests (ABA) increases the surface area of reactive sulfide and neutralizing minerals and releases reactive sulfides that are en-

closed in inert minerals and may consequently indicate net neutralization potentials significantly different from that of the tailings material in situ (EPA 2003).

Common mistakes made in data interpretation include the following (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003):

- information gaps in the data, such as insufficient numbers of sample results;
- drawing definite conclusions without the supporting data;
- considering laboratory results in isolation from other important evidences (e.g. the conceptual site model or the field notes);
- assuming contaminant results below detection limits implies the contaminant does not exist in the soil;
- using an inappropriately site investigation strategy (e.g. using judgemental sampling);
- collecting an unrepresentative sample.

Measurement errors

- transposition errors
- wrong sample marking
- wrong calibration
- sample contamination
- losses
- instrument instability
- variability of blank
- sample variability

Sampling errors

- particles of the selected area have no equal chance of selection
- inappropriate sampling procedure
- improper labelling of samples (i.e. illegible, missing etc.)
- improper handling and storage of samples
- decontamination of sampling tools is not undertaken, leading to cross contamination between samples
- kinds of sampling errors:
 - fundamental, grouping and segregation errors (caused by heterogeneity)
 - delimitation and extraction errors (choice of sampling tools)
 - preparation errors (after sampling)
 - cycles and trends (concentration changes with respect to time/space)

5.10.2 PREVENTION, CALCULATION OR ESTIMATION OF SAMPLING ERRORS

Concerning composite samples (SMITH et al. 2000):

- The fundamental error resulting from the heterogeneity of the sampled material cannot be eliminated, but it can be estimated prior to sampling. Based on the results efforts to minimise this error can be undertaken. Important factors that have to be taken into account are heterogeneity, particle

size, and sample mass. The fundamental error (FE) can be estimated by the following (premise: the mass of the population is greater than ten times the mass of the sample):

$$FE^2 = \frac{clfgd^3}{M_s}$$

where:

FE^2 = a relative variance	l = the liberation factor
M_s = the sample mass [g]	f = the shape factor
c = the mineralogical factor	g = the granulometric factor
	d = the maximum particle size [cm]

- The grouping and segregation error can be minimised by collecting as many small increments as practically possible (grouping factor). The segregation factor should be kept in mind when collecting samples and is much more difficult to minimize, as affected by differences in particle density, particle size, particle shape etc.

6 BASICS OF DATA INTERPRETATION

“Data from instruments and from visual inspection are only as useful as the capacity of the staff to interpret them correctly and rapidly and to be able to respond accordingly” (ICOLD 1996b).

Data generated from site investigations should be related to the conceptual site model based on historical and screening data, to see if the information makes sense in relation to the anticipated model conditions. Analytical and field results should enable the conceptual site model to be refined. The achieved information should be assessed to determine the location, extent, trends and movement of the contamination (MINISTRY FOR THE ENVIRONMENT - NEW ZEALAND 2003).

The interpretation of site data requires a review of all information sources, including the conceptual site model, field data and analytical results. At this, the limitations in sampling and analytical options, and therefore the uncertainty in the resulting data, must be identified, understood and considered. The validity of the data must be assured and any uncertainty in the accuracy of the data explained.

7 SITE CHARACTERISATION REPORT

The main task of the report is to provide the appropriate and sufficient basis for the accurate assessment of the site under investigation. Therefore, the vast amounts of obtained data must be presented in a way that enables the user to get a clear understanding of the location, especially of the extent and the behaviour of existing contamination. The report should be a useful tool for getting easy access to the required data including the appropriate interpretation.

The report must define the purpose of the site characterisation, with respect to the objectives of the overall investigation. The chosen approach (if possible, with reference to used legal guidelines or other directives) has to be described in detail including:

- listing of evaluated sources for existing data, such as site history etc.;
- sampling strategy, including sampling pattern, number of samples, types of samples;
- field or laboratory methods;
- data quality objectives and control procedures;
- statistical evaluation method (mean, median, mode).

The data presentation should be made in an adequate mode, like lists, tables, diagrams, maps etc., to ensure that every information given can be readily and exactly assigned, and this includes:

- data from site history research, enclosing old site layout plans, photographs, material safety data sheets and permits in the report appendix;
- samples identification number with sampling location and date;
- analytical results from field and laboratory, also minima, maxima, mean, median, standard deviation, distribution.

A categorisation of the tailings material such as “Acid Consuming Material”, “Non-Acid Forming, Low Sulfur”, “Non-Acid Forming, High Sulfur”, “Potential Acid Forming, Low Capacity” , “Potential Acid Forming, High Capacity” (LEE 1999) may be beneficial in regard to a standardised risk assessment. Beside this, results and their interpretation must provide information on:

- contaminant sources;
- migration pathways;
- type and extent of existing contamination at the site in comparison to relevant thresholds and background levels;
- hot spots and gradients of contamination (contamination pattern);
- potential of further contamination of areas at the site or in the surrounding.

8 SUMMARY OF SITE CHARACTERISATION APPROACH

A summarisation of the presented approach concerning an adequate site characterisation is shown in the following flowchart (Fig. 2).

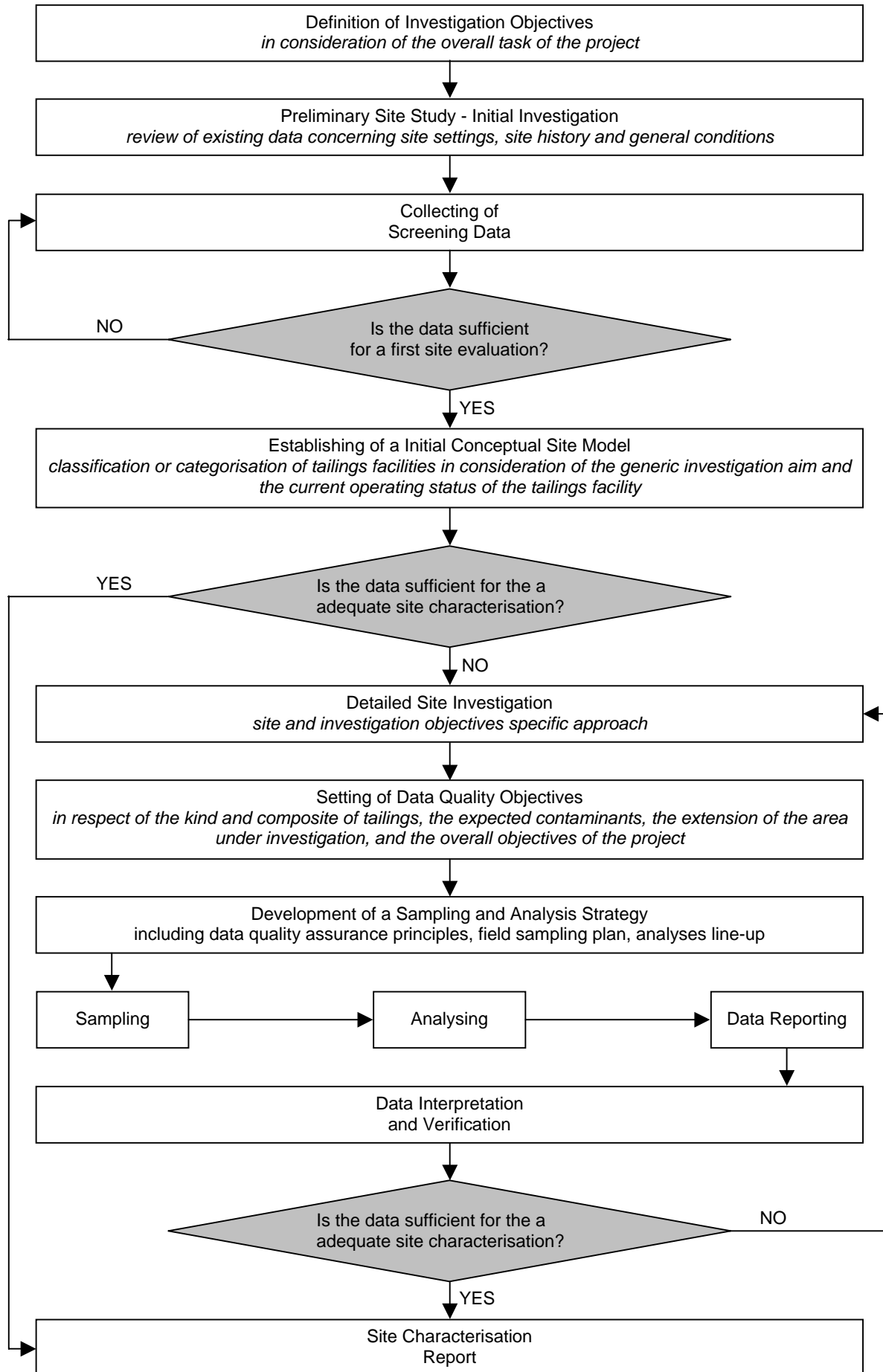


Fig. 2: Flowchart for site characterisation.

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APPENDIX: Matrix of Methods for the Characterisation of Tailings Facilities

Method	Standards (examples)	Characterisation of tailings material							Requirements			Location		Data Quality		Costs	Remarks	Reference
		Mineralogy	Acid generating potential	Heavy/trace metals	Organic content	Water content	Soil Mechanics	Static Liquefaction Behaviour	Sample	Equipment	Staff	On-site	Laboratory	Screening data	Specific data			
X-Ray Diffraction (XRD)	n/a	x						d	xxx	t		x		x	xxx			
Thermal Analysis (TA)	n/a	x						d	xxx	t		x		x	xxx			
Scanning Electron Microscopy (SEM)	n/a	x		x			x	d/u	xxx	t		x		x	xxx			
X-Ray Fluorescence Spectrometry (XRF)	n/a			x				d	xxx	t		x		x	xxx			
Loss on ignition (550°C)	Germany: DIN 18128 UK: BS 1377-3,4 (440°C)				(x)			d	x	u		x		x	x	not suitable in clay-rich samples		
TOC (total organic carbon) analysis	UK: BS 1377-3 ,3				x			d	xxx	t		x		x	xx			
TIC (total inorganic carbon) analysis	ASTM E 1019-94	x	x					d	x	t		x			x		LAPAKKO	
Carbonate content determination by volumetric gas analysis	Germany: DIN 18129	x						d	x	u		x		x	x			
Carbonate content determination by acid dissolution and NaOH titration	UK: BS1377-3,6	x						d	x	t		x		x	x			
Acid digestion	Germany: DIN 38414-7	x		x				d	xx	t		x		x	xx			
Metals mobilisation potential estimation by sequential chemical extractions	n/a	x		x				d	xx	t		x		x	xxx			
Contaminants mobilisation potential by acid extraction test	US EPA TCLP (Method 1311) British Columbia SWEP			x				d	xx	t		x		x	xx			
Contaminants mobilisation potential by de-ionised water extraction test	British Columbia Modified SWEP Germany: DIN 38414-4 European Standard EN 12457/1-4			x				d	xx	t		x		x	xx	deionised water extraction tests more closely approximate in-situ conditions (EUROPEAN COMMISSION 2003)	EUROPEAN COMMISSION 2003 - BAT EPA 2003	
Contaminants mobilisation potential by dynamic extraction tests	Swiss TVA Eluate test			x				d	xx	t		x		x	xx			
Field Leach Test	HAGEMAN and BRIGGS 2000			x					x	u	x		x		x		SMITH et al. 2000b	

Sulfur concentration and sulfur species determination by sequential chemical extractions			x						d	xx	t		x		x	xx		LAPAKKO 2002
Balance between potentially acid-generating and potentially acid-neutralizing minerals by static predictive test			x						d					x		x	no information on the quality of effluent in the future (EPA 2003)	WHITE et al. 1999
Acid Base Accounting (ABA) - static test			x						d	xx	t		x		x	xx	represents the sulfur contained in acid-generating iron-sulfide minerals in the sample	
Net Acid Production (NAP) / Net Acid Generation (NAG) - static test			x						d	xx	t	x	x		x	xx	does not require sulfur determination	
Determination of acid consumption and acid production rates - kinetic test			x						u	xx	t	x	x		x	xxx	kinetic tests simulate the specific environmental conditions by accelerating the natural weathering rate	EPA 2003
Assess the presence of soluble acid salts			x						d	x	u	x		x		x	paste pH	LAPAKKO 2002
Acid Concentration Present (ACP) test			x						d	x	t		x	x				LAPAKKO 2002
Oven drying (105°C)	Germany: DIN 18121,1 UK: BS 1377-2,3					x	x		d	x	u		x		x	x		
Particle density	Germany: DIN 18124 UK: BS 1377-2,8						x		d	x	t		x		x	x		
Grain size distribution	Germany: DIN 18123 UK: BS 1377-2,9						x		d	x	t		x		x	x		
Hydraulic conductivity estimated by empirical relationships							x				t		x	x		x	set up by e.g. BAYER and HAZEN	
Hydraulic conductivity determined by column tests	Germany: DIN 18130,1 UK: BS1377-5,5						x		d/u	xx	t		x		x	xx		
Hydraulic conductivity determined by hydraulic consolidation and triaxial cells tests	UK: BS1377-6,4+6						x		u	xx	t		x		x	xx		
Water absorption	Germany: DIN 18132						x		d	xx	t		x		x	x		
Plasticity (ATTERBERG consistency limits)	Germany: DIN 18122 UK: BS1377-2,4+5						x		d	x	t		x		x	x		

Compactibility by Proctor test	Germany: DIN 18127 UK: BS1377-4,3 ASTM D698							x		d	x	t			x		x	xx
Consolidation characteristics	UK: BS1377-5,3							x		u	x	t			x		x	xx
Shear strength	Germany: DIN 18137 UK: BS 1377-7 & BS 1377-8							x	x*	d/u	xx	t			x		x	xx

n/a = not available

Requirements: Sample: d = disturbed, u = undisturbed
Equipment: complexity low (x) to high (xxx)
Staff: t = trained, u = untrained

Costs: low (x) to high (xxx)

* Static liquefaction behaviour is determined in consolidated undrained triaxial tests. Great operator skill is required to prepare/handle very loose tailings samples. Costs: xxx