TAILSAFE

Sustainable Improvement in Safety of Tailings Facilities

TAILSAFE

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Report

Implementation and Improvement of Closure and Restoration Plans for Disused Tailings Facilities

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Tailings Management Facilities – Implementation and Improvement of Closure and Restoration Plans for Disused Tailings Facilities

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Other reports of the TAILSAFE project:

Witt, K.J. & Schönhardt, M. (Eds., 2004): Tailings Management Facilities – Risks and Reliability. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 176 p.

Engels, J. (Ed., 2004): Tailings Management Facilities – Intervention Actions for Risk Reduction. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 150 p.

Witt, K.J. & Wudtke, R.-B. (Eds., 2004): Tailings Management Facilities – Implementation and Improvement of Design and Authorisation Procedures for Proposed Tailings Facilities. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 24 p.

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Engels, J. (2004): Risk Reduction Actions for Substandard or Impaired Tailings Facilities. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 29 p.

Kreft-Burman, K., Saarela, J. & Anderson, R. (2005): Tailings Management Facilities – Legislation, Authorisation, Management, Monitoring and Inspection Practices. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 66 p.

Niederleithinger, E., Kruschwitz, S. & Martin, T. (2005): Non-Destructive and Minimally Intrusive Methods for the Investigation and Monitoring of Tailings Impoundments. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 51 p.

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1. Introduction

Mining operations are finite economic activities, which are usually relatively short term. The tailings that remain after mining of an ore deposit is complete are often the most visible remaining signs of the mining activity. Together with the mine waste rock and the mine openings they are recognised as the “legacy” impacts of mining. The tailings or mine waste disposal facility has proven the most contentious component of mining activities and has represented the source of significant environmental and economic impacts due, in the majority of cases, to poor management. The primary aim in the past has been to provide a well-engineered structure into which the tailings can be deposited without a great deal of attention being given to closure requirements or issues related to long term management of the storage facility. In the past 20 to 30 years it has been increasingly recognised that for a mining project to contribute positively to an area’s development in any lasting way, closure objectives and impacts must be considered from project inception. The tailings facility needs to be engineered for closure so that stability and environmental performance criteria can be achieved.

In this report, the main issues to be considered for the closure of disused tailings facilities are described. Control technologies with emphasis on alternative covers for the stabilisation of tailings deposits in order to ensure the environmental safety in the long term are also reviewed. A case study, involving the issues addressed and the measures implemented for the reclamation of tailings ponds in Pécs, Hungary is finally presented.

2. Closure objectives and criteria

In recent years, there have been a number of studies to consider the standards to be achieved on closure in USA, Canada, Australia and, most recently, in Europe. Generally, the major issues to be considered for the reclamation of mining/milling components include the long-term (a) physical stability, (b) chemical stability and (c) land use. Based on the regulations developed in Canada (Doran and McIntosh 1995), after closure, the waste disposal areas of a mine site should be physically stable under extreme events such as floods, earthquakes and perpetual disruptive forces including wind and water erosion, so that they do not impose a hazard to public health and safety or the environment. Regarding the chemical stability, leaching of contaminants contained in the wastes and migration into the environment should not endanger public health or safety, nor exceed water quality objectives in downstream watercourses.

Based on the guidelines prepared by the Department of Minerals and Energy, Western Australia (DME 1999), decommissioned tailings storage facilities must be *safe*, *stable* and *aesthetically acceptable*. A facility is considered to be safe when the retaining embankment will not be breached and where the contained tailings are not able to contaminate the surrounding areas. The surface and ground water should not be adversely affected as a result of either liquor or metals leaching from the structure. Stable means that the decommissioned tailings facility should not erode at an excessive rate. Finally, the facility should blend into the landscape and suitable self-sustaining vegetation should cover the visible portions of the structure.

The fundamental mine closure design criteria, as described in the relevant study performed by MIRO (1999) are given in Table 1.

Table 1: Closure design criteria for the mine closure planning process (MIRO 1999).

a/a	Issue	Closure design criteria
1	Physical stability	Physical stabilisation of man-made structures in order to pose no risk in terms of safety or environmental impact.
2	Chemical stability	Chemical stabilisation of physical structures, so that to provide no contamination problems to the environment or risks to public health.
3	Biological stability	Restoration of the biological environment to a balanced, self-sustaining ecosystem typical of the area, or left in such a state so as to encourage natural rehabilitation and development of a biologically diverse, stable environment.
4	Hydrology and hydrogeology	Prevention of contaminants migration downstream (surface and ground waters).
5	Geographical and climatic influences	Fulfilment of the demands and compliance with the site characteristics including climatic (e.g. rainfall, storm event) and geographic factors (proximity to residential areas, topography, accessibility).
6	Local sensitivities and opportunities	Optimisation of the opportunities for restoring the land. Upgrading of the land use, wherever appropriate and/or economically feasible.
7	Land Use	Final land use compatible with the surrounding area and the local community requirements.
8	Financial Assurance	Adequate and appropriate financial assurance to ensure implementation of the mine closure plan.
9	Socio-economic considerations	Encouragement of alternative opportunities for local communities. Maximisation of positive socio-economic implications.

A requirement to draw up closure plans for mine waste management facilities in order to ensure that closure operations form an integral part of the overall exploitation plan of the operator is contained in the recent proposal for a European directive on the “Management of waste from the extractive industries” (COM 2003, 319 final). In Article 12 of the proposal, the tasks that have to be carried out by the operator and the role of the competent authority in supervising closure and aftercare procedures are laid out. The operation shall control the physical and chemical stability of the facility and minimise any negative environmental effect, in particular with respect to surface and groundwater.

2.1 Physical stability

Stability after closure is a major concern in tailings dam engineering. Many of the physical considerations pertaining to the closure of a tailings facility are the same as those during its operation. The differences are, however, related to the longer time span for which structures need to remain stable. Long-term normally means until the next “ice age” or a couple of thousand years (BREF 2004). Thus the difference in time scale is likely to be a minimum of an order of magnitude such as 200 years, or as much as 2,000 years of stability for closure as compared to 20 years of stability for an operating mine.

In the long term, a tailings deposit and its control structures are mainly subject to two classes of disruptive forces (Robertson and Clifton 1987):

(a) short duration extreme events such as floods, earthquakes, fires and tornadoes, and
(b) perpetual forces such as water and wind erosion, and frost action.

These disruptive forces are summarised in Table 2. A description of these processes and subsequent environmental impact was also presented in TAILSAFE WP2 report "*Analysis: Risk and Reliability*".

Table 2: Issues affecting physical stability of the tailings dams.

Factors	Consequences
Extreme events	
• High precipitation and floods	• Overtopping/dam failure and losses of tailings
• Earthquakes	• Liquefaction of tailings
Disruptive forces	
• Wind erosion	• Major release mechanism from exposed tailings
• Water erosion	• Flood erosion • Sheet and rill erosion of dam, covers • Gully erosion, major cause of instability of tailings surface, covers and dam
• Frost action	• Ice accumulation, frost penetration

2.1.1 Extreme events

Tailings Management Facilities (TMF) are subject to extreme events, which, because of the long period of post closure interest, have a much greater probability of occurrence than during the operating period of the mine. Further, the consequences (economic, environmental and socio-economic) of structural failures of tailings dams are also oftentimes large.

Large precipitation events represent one of the most likely causes of tailings impoundment failure. Failure during such events is also likely to result in large losses of tailings to the environment. Thus the selection and computation of design floods is an important part of tailings dams and associated structures (e.g. spillways, ditches, diversions, etc.). Non-critical structures are typically designed to accommodate the 1 in 100 year flood event while structures that would cause large, but not catastrophic impacts, or are critical to the operations of specific facilities would require design to accommodate the 1 in 1000 year event. Those structures for which failure could result in casualties or cause catastrophic environmental impacts should be designed for the probable maximum flood (PMF) (Robertson and Shaw 2004).

Dynamic loads, due to earthquakes, may result in the liquefaction of low density saturated tailings or uncompacted saturated portions of granular embankments or embankment foundation material. It is typical for long term closure planning, that measures will consider larger events where the consequences of failure would be catastrophic, i.e. 1:10,000 year or maximum credible earthquake (MCE). In high seismic areas, use of construction methods, which result in a low dynamic stability (such as upstream construction using tailings) may be inappropriate (Robertson and Clifton 1987). The propensity for upstream tailings dams to experience large-scale liquefaction flowsliding during moderate to severe seismic shaking is well known from a number of such failures and resulting fatalities worldwide. However, these flow failures have been observed to occur only for such dams in active operation at the time of the earthquake. By contrast, their stability improves markedly when they become inactive and surface water is no longer present (Vick 2001).

A general safety factor for dams and heaps during operation and upon closure of 1.3 is considered as BAT (BREF 2004). For dams designed to permanently retain water, a safety factor of 1.5 is considered to be sufficient for dynamic stability.

In order to analyse the safety and to predict the behaviour of a dam under extreme events, it is necessary to anticipate the evolution of properties of materials and to assign parameters to model structures formed by different soils. Tailings dams, which have been built by conventional hydraulic fill methods normally, involve unknown characteristics such as final geometry and properties of the soil structures created by mode of deposition. Techniques, sequences and environmental conditions at the time of deposition obviously have strong influences on the mechanical parameters, which control long-term behaviour of the deposits. However, it is always difficult to get detailed construction and operations reports good enough to reproduce the as-built conditions. Other major considerations relate to the hydrogeological conditions of the site, effectiveness of the drainage and water diversion works and the resulting flow nets, and predictable pore water pressure variations. These conditions are variable over the years depending upon the intensity of precipitation and seismic activity.

Therefore, sub-surface investigations and dynamic analyses are required in order to model the structures and to study the stability after abandonment. Different methods are used to determine soil profiles and properties, phreatic levels and pore water pressures. Mathematical procedures are also available for calculations of stresses and displacements inside the deposits. A detailed geotechnical investigation of the Piuquenes tailings deposit in Chile was performed aiming at a realistic evaluation of dam stability after abandonment (Troncoso 1998). The crucial properties of the soils, such as shear strength under static and seismic loading as well as the effects of consolidation and age were determined. The analysis of the long-term stability of the structure and the determination of corresponding safety factors or levels of risks allowed the design of appropriate rehabilitation measures to ensure environmental protection.

2.1.2 Perpetual disruptive forces

During the long-term phase, dams can be damaged by slow deteriorating processes, such as wind and water erosion, frost, ice, seepage etc.

Wind erosion is a major problem related to tailings storage facilities and is a specific concern for nearby communities. Beaches of tailings storage facilities contain fine sand or silt size particles that can easily be removed by wind. Blowing dust can result in impacts on health through breathing, etc. as well as agriculture through metals uptake by plants. Wetting of the beach or using special products to stabilise the tailings surface has been implemented for temporary wind erosion and dust control. Long-term stabilisation requires the establishment of a gravel cover or vegetation.

Water erosion is probably the single most severe cause of tailings dam instability. Erosion can take the form of flood erosion of the diversion workings, or sheet and gully erosion of the impoundment surface and embankment slopes. A substantial portion of total erosion occurs during extreme precipitation and flood events. The probability of failure will depend on the criteria used to design the structure, and the degree of scour, sedimentation and/or blockage which has occurred. Methods for the evaluation of erosion risk and appropriate design are well developed. Gully erosion has been observed to be a major cause of instability of tailings surfaces and embankments.

In areas where continuous or discontinuous permafrost develops, and in areas of severe winter cold, frost action may be a severe cause of instability. The effects of freezing temperature on tailings impoundment stability include ice accumulation and frost penetration (Robertson and Clifton 1987).

Ice accumulation may result in blockage of the diversion structures or outlet works, with a consequential risk of erosion along the displaced flow channel during the early spring melt. Freezing of drains may result in a build up of pore pressures in embankments resulting in slope failure. Accumulation of frozen tailings prevent drainage and hence the dissipation of pore pressures and the consolidation of the tailings. In non permafrost areas, thawing of the contained ice may result in long term seepage and elevated pore pressures in the tailings long after construction has ceased. Large consolidation settlements may occur after close-out. Such settlement will affect the drainage pattern on the surface of the impoundment and may result in cracking of any cover layers placed on the tailings.

Frost penetration may increase the permeability of the tailings (Robertson 1987). Frost susceptible cover materials subjected to freezing will develop ice lenses and a fissured structure, which on thawing increases the permeability of the cover. This represents a severe failure mechanism for covers designed to limit infiltration into the tailings. Frost penetration may also block subsurface drains, preventing drainage and causing pore pressure increases.

For dams designed to permanently retain water, the slow deteriorating process that most likely is of greatest importance for the stability is the seepage through the dam. Seepage through the dam may cause inner erosion, which is a common cause of damage to large hydropower dams. However, it is possible to prevent inner erosion if the inclination of the hydraulic gradient (i.e. the pore pressure line) is as low as in natural soil formations that are stable against groundwater flow. Generally, a soil slope is stable against internal erosion if the inclination of the hydraulic gradient is less than half of the friction angle of the soil material.

Damages by erosion, temperature and vegetation can be avoided by using long-term stable materials in the construction of the dam and by constructing the slopes of a sufficiently low angle. Experiences and studies of natural formations similar to tailings dams indicate that a slope flatter than 1:3 (V:H) has so far proven stable for water and wind erosion, frost and weathering for the last 10000 years (i.e. since the last ice-age). An angle flatter than 1:3 will also support vegetation, which will subsequently decrease the impact of slow deterioration actions (BREF 2004).

2.1.3 Other issues

Other factors that might be considered in the context of tailings dam design and dam safety practices required for perpetual stability include the uncertainty in the magnitude of extreme events, cumulative damage, climate change and geologic hazards (Vick, 2001).

The design values regarding floods and earthquakes are established within the framework of the hydrometeorological and seismotectonic understanding of the region, and are thus a function of the state of knowledge at the time they are derived. However, this state of knowledge continually changes as understanding of technical factors improves and occurrences of large floods and earthquakes accumulate. So the original design estimates change over time as well, but they will always increase in magnitude and never reduce. Upgrading of the tailings dams under post-closure circumstances might be thus necessary to sustain the extreme event estimates that future knowledge provides.

A related factor involves *cumulative damage* from repeated occurrences of extreme events, or progressive processes like internal erosion, that degrade dam stability over time. For conventional dams, drawdown of the reservoir can be required to repair major damage and is also an important emergency response. But a reservoir containing tailings solids cannot be reduced in level. Moreover, a tailings dam will experience repeated occurrences of extreme events during the indefinite future, their number depending on time and recurrence rate which for major earthquakes in some mining regions is on the order of only hundreds of years. An example of the cumulative effects of seismic shaking is provided by La Villita Dam in Mexico, which has experienced progressively increasing crest settlements during four separate episodes of major seismic shaking in just 30 years. Cumulative damage also results from simple deterioration with age. No concrete structure – spillway, decant facility, or tunnel lining – lasts forever without continuing maintenance and repair.

The effects of long-term *climate change* are also of intense interest and great uncertainty. For a tailings dam to remain stable in perpetuity, accurate prediction of the influence of these changes on floods and spillway capacity is somehow required, something that even climate experts are not able to do. Climate change may also affect both physical and chemical stability in other ways. For example, the reduction in the acid generation reaction rates at some mines in arctic and sub-arctic regions are relied upon to frozen conditions, where certain tailings dams also depend for stability on the presence of frozen ground. Permanent submergence also requires sufficient water, even during sustained drought, notwithstanding any future changes in climate. It is therefore important to evaluate the potential effects of climate change if this may be relevant to the long-term behaviour of the chosen management option.

While tailings dams are designed to accommodate the *geological hazards* known to exist at the time they are constructed, in the indefinite future they will eventually be subject to the full suite of geomorphic processes operating at their sites (e.g. landslides, rock avalanches, volcanic activity, karst collapses). Like the occurrence of extreme events, the damaging effects of these processes are only a question of time and recurrence rate, a factor particularly difficult to predict for most large-scale geological phenomena. Even the more benign processes of alluvial deposition will eventually fill water conveyance facilities unless they are continually cleared of sediment and debris.

Based on the above, long-term dam safety depends to a large extent on the presumption of continuing maintenance, modification, and repair, and it is difficult to assure stability in the long term without these activities in perpetuity.

2.2 Chemical stability

In the past mine rehabilitation requirements were restricted mainly to measures required to ensure physical stability. This state of mind led to the construction of stable tailings embankments and spillways, and the prevention of public access as the sole rehabilitation requirement in countries where rehabilitation requirements were in force. More recently, there has been an increased recognition of the potential for chemical instability. This has come about by the realisation that the leaching of contaminants from the mine site and their entry into the local water regime represents a major impact on the environment. The need to demonstrate chemical stability, or achieve sufficiently low release rates, so that the downstream environments are not adversely affected, is now critical. A rehabilitated, disturbed site must be both physically and chemically stable and must also achieve a land use similar to its previous use or to another acceptable condition.

Chemical stability issues include Acid Mine Drainage (AMD), the leaching of metals, the precipitation of metals, cyanide release, radionuclides migration and the flushing of mill reagents and other chemicals, as given in Table 3. The major contaminants commonly found in tailings are given in Table 4.

Table 3: Issues affecting chemical stability of the tailings dams.

Factors	Consequences
• Chemical changes (acid generation, metals leachability, precipitation of salts)	• Surface/ground water contamination • Drain plugging due to salts deposition • Solution and transport of soluble products may result in increased seepage and possibly piping
• Weathering of cover materials, liners, riprap	• Degradation of protective layers

Table 4: Contaminants commonly found in tailings (UNEP/WHO 1998).

Base Metals	Al, As, B, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, and Zn
Combination of Pollutants	Thiosulphates, nitrates, hydroxides, sulphates, etc.
Reagents	CN, organic reagents, oils
Other	Pesticides, herbicides, paints, solvents, PCBs, etc.

Chemical changes in the nature of the tailings and the leachates may affect both the chemical and physical stability of TMF. Solution and transport of soluble products can result in removal of mass material from its original placement location and re-deposition elsewhere. Furthermore, preferential seepage channels caused by solution may result in increased seepage and possibly piping. Deposition of salts (e.g. gypsum and ferrous salts) has been common cause of drain plugging in tailings dams. Chemical weathering of cover materials, liners and riprap may also result in the long-term degradation of protective layers (Robertson and Clifton 1987).

The major contaminants that may be contained in tailings, potential pathways of migration and subsequent environmental impact were reviewed in TAILSAFE WP2 report Analysis: Risk and Reliability. These processes affecting the chemical stability of tailings facilities in the long term are briefly presented in the following paragraphs.

When discussing chemical stability, the first and major environmental problem facing the minerals industry today is *Acid Mine Drainage* (AMD) or Acid Rock Drainage (ARD). The AMD phenomenon is associated with base metal, gold and uranium mining operations as well as the coal and lignite mining industry. AMD is produced by the oxidation of sulphide minerals, mainly pyrite and pyrrhotite, in the presence of air, water and bacteria, resulting in the formation of acidic solutions with increased concentrations of sulphate anions and dissolved metals. The overall pyrite oxidation process can be described by Equation (1).

$$FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (1)$$

A great deal of research has been carried out to improve the understanding of chemical stability issues, including work on acid generation prediction, prevention, treatment and mitigation. There are few (if any) areas in mining where so much information is available. One of the most serious aspects of acid drainage is its persistence in the environment. Tailings that have not been properly deposited or rehabilitated can produce acid drainage for hundreds of years or more after mining has ceased. Once the process of acid generation has started it is extremely difficult to stop and can effectively kill most living organisms in an entire water system for years, turning it into a biological challenge and a huge economic burden. Measures for the control of chemical reactions and the treatment and control of drainage, must be site specific and specific to the source and the type of contaminant. It is therefore a very complex problem, which has to be very carefully addressed.

Processes involving the use of *cyanide*, such as gold extraction if not managed correctly can also have damaging effects on the environment. The effects include the killing of birds in barren ponds as well as untreated tailings supernatant; leakage from lined facilities; damage to the environment if released during failure of tailings disposal facilities. In order to address the concerns about cyanide management in the mining industry the Gold Institute, over the last two years, managed (on behalf of UNEP and ICME) the development of a cyanide management document known as the Cyanide Code. A multi-stakeholder committee was established to review and address the large variety of issues associated with cyanide transportation and use. The Code was released in mid-March of 2002 and is ready for implementation at individual mine sites (International Cyanide Management Institute 2002).

The processing of uranium ores as well phosphate rocks, bauxite and coal has the potential to produce tailings with *radioactive contaminants*. Uranium tailings pose a risk to health because (Diehl, 2004):

- Radium in tailings decays into radon, a gaseous radioactive element which is easily transported in air and the radioactive decay products of which may lodge in the lungs;
- Individuals may be directly exposed to gamma radiation from the radioactivity in tailings; the exposure to radioactive and toxic substances may cause cancer and other diseases, as well as genetic damage and teratogenic effects; and
- Radioactive and toxic substances from tailings may leach into water and then be ingested with food or water, or inhaled following aeration.

A number of other chemicals may be used in mining and mineral processing the most common of which are sodium ethyl xanthate, methyl isobutyl ketone, sulphuric acid, sodium hydroxide, copper sulphate, hydroxy oxime and polycarboxylic acid. The majority of these are used in the flotation process or to control or accentuate leaching. Residual quantities of these chemicals are often discharged with the tailings.

Chemical stability is mainly associated with impacts on surface and ground water quality. Typically, criteria or standards are applied to water being discharged, or at some compliance point within the receiving stream or aquifer. Such standards or objectives are threshold indicators (not to be exceeded) in a scalar value of concentrations or load limitations for receiving streams and aquifers. Other 'indicators' of surface water include seep coloration, odour and taste. While this is more often an aesthetic issue, coloured seeps on mine sites are often indicative of certain chemical signatures.

2.3 Biological stability

The biological stability of the closed site is closely related to its final land-use, whereas the stability of the surrounding environment will be primarily dependent upon the physical and chemical characteristics of the site. All three are linked because biological stability may significantly influence physical or chemical stability. For example, plant roots will inhibit erosion by binding the soil surface, and the development of a healthy plant cover over a wetland treatment area will increase the surface depth of organic matter, thus creating the anoxic conditions necessary for water treatment. The rehabilitation of most sites involves the revegetation of large areas of restored land, which can often be of a poor quality in terms of sustained plant growth. It is important, therefore, that the methods of amelioration and cultivation of the soils or soil forming materials, together with the species chosen result in the development of a sustainable plant cover. This should be appropriate to the chosen land-use and may play an important part in maintaining the physical and chemical stability of the site, for instance by stabilising the soil cover and preventing erosion. Monitoring is aimed at demonstrating that not only plant growth has been successful in the first instance, but over a period of several growing seasons has developed into a self-sustaining plant community.

Biological disruption affecting stability of the dams would include root penetration, burrowing intrusion and actions by animals and humans, as given in Table 5.

Table 5: Biological factors affecting stability of the tailings dams

Factors	Consequences
• Root penetration	Roots may penetrate • Drains resulting in clogging • Low permeability layers, increasing infiltration through covers or piping in dams
• Burrowing intrusion	• Burrowing intrusion by insects and animals may damage the low permeability cover system • Burrowing along phreatic line in fine material may induce piping failures

Conventional safety practice recognises the detrimental effects of burrowing animals and root penetration as matters that need to be addressed with continuing maintenance. Roots may penetrate low permeability layers and also create seepage channels, which would increase infiltration through covers, or piping in embankments. Extensive root development in moist, permeable drains or drainage layers may also result in clogging of the drains. Burrowing intrusion by insects and animals has the potential in the long term, of significantly altering the hydraulic conductivity of low permeability capping layers. Other problems may be more unexpected. For example, as the country's national symbol, the beaver is ubiquitous to Canada, and its habits are well known to engineers and biologists alike. Its propensity to undertake its activities in response to the sound of running water has been acknowledged as a serious long-term closure issue for tailings dams as it builds dams which can cause the blockage of diversion facilities, and indeed this has been documented as a cause of tailings dam failure in the past. In Europe, it should be noted that the European beaver, which became extinct in Sweden in the 1870s, was reintroduced in the 1920s and is now thriving successfully (Vick 2001).

2.4 Land use

Mining is intrusive and mined lands can often not be returned to their original use. If possible, they should be turned to an acceptable alternative use. The general successive use of a closed site is determined by the following factors (BREF 2004):

- pre-mining or current land use surrounding the site
- any expected future changes in surrounding land use
- the reasonably expected post-operational use of the mine site
- viability of re-using the site infrastructure and facilities
- the extent of any environmental impacts
- the need to safeguard against physical, chemical and biological hazards (both anthropogenic and naturally occurring).

It must be stressed that the first objective is public health and safety in determining the rehabilitation requirements and the utilisation of the land in the future. The hazards that are remaining on the rehabilitated site should be of the same, or of lesser magnitude, to the hazards typical of the area prior to the mining development. There are a number of different options that are considered for most sites, including:

- natural recolonisation of the site by local vegetation
- planting of commercial forestry plantations
- development for agriculture
- encouragement of alternative industrial activities
- use of infrastructure facilities as part of the commercial development in the region.

The tailings dams often represent new hill-like structures and are usually rehabilitated so that the area impacted will be amenable to support a balanced diversity of flora and fauna. The physical and chemical characteristics of the tailings material should be available, as these will dictate the extent to which vegetation and landscaping is practicable. There are many features, which may inhibit the development of vegetation on tailings dumps, all of which must be addressed in planning and designing the rehabilitation of the structure. Some of the characteristics, which should be taken into consideration while planning and designing the rehabilitation programme, include (UNEP/WHO 1998):

- Community considerations and concerns, and ability to participate in rehabilitation and long-term maintenance
- Extremes of pH and concentration of heavy metals and salts
- A lack of essential plant nutrients and microbiological organisms
- Natural availability of local plant species and fauna that might enter the site
- Texture and structural characteristics of the soil which may limit aeration and infiltration
- Availability of sub-soil and soil which may be used to remediate the site
- Local climatic conditions (rain/temperature/wind)
- Geological conditions
- Particularly in arid and semi-arid, high temperature areas, the levels of reflected light or heat absorption on dark or light tailings can cause physiological stress to vegetation

3. Closure technologies

3.1 General

Table 6 provides the rehabilitation methods and the control techniques for the physical and chemical stability and land use of tailings facilities. Furthermore, potential control technologies for chemical stability are summarised in Table 7.

In assessing rehabilitation alternatives there are a number of criteria that should be considered including (UNEP/WHO 1998):

- The ability to meet expected environmental conditions
- The cost effectiveness of the programme
- The certainty of the present technology and techniques used and their anticipated long-term performance
- The maintenance and monitoring requirements.

Current best management practice requires the placement of a cover onto tailings at closure of the facility. The design and construction of a cover system often represents the single biggest issue of TMF closure, with respect to environmental impact and cost but also public and regulatory scrutiny. Given that the different types of covers used in the closure of TMF are reviewed in this chapter. Relevant data were also given in TAILSAFE report WP3: Intervention actions, where the intervention actions implemented to reduce the risk and provide long term physical and chemical stability of tailings impoundments were described.

Table 6: Control techniques for physical, chemical stability and land use of TMF (modified from UNEP/WHO 1998, MIRO 1999).

Issues	Objectives/ Criteria	Control technologies
Physical stability		
Tailings		
• Dust • Water erosion	• Acceptable atmospheric dust levels • Integrity of erosion control measures • Mining, civil engineering and construction standards	• Erosion resistant covers of vegetation, soil, riprap, water, rock
Dams		
• Erosion • High phreatic surface • Slope failure	• Mining, civil engineering and construction standards • Integrity of erosion control cover	• Buttressing • Erosion resistant cover • Increase freeboard and/ or upgrade spillway to prevent overtopping
Water management structures		
• Weathering • Destruction of permanent structures - spillways - decant towers/ pipes • Drainage disruption	• Remove or establish long-term stability • Integrate with local drainage	• Remove or plug/backfill structures • Diversions and spillways designed for long-term stability • Plug/seal decant lines through embankments • Define and provide for long-term monitoring and maintenance • Avoid ongoing operation where possible
Chemical stability		
Tailings		
• Acid drainage • Metals leaching • Mill reagents	• Water quality standards	• Prevent sulphides oxidation • Control migration of contaminants • Collect and treat acidic and contaminated waters
Dams		
• Acid drainage • Metals leaching	• Water quality standards	• Stabilise acid generating or contaminated materials
Land use		
• Productivity of land • Visual impact	• Return to appropriate land use/ Biological stability, Successful plant growth	• Re-contouring, capping and establishment of vegetation • Flooding and construction of wetlands

Table 7: Potential control technologies for chemical stability (Brodie et al. 1992).

CONTROL TECHNOLOGY	Acid drainage	Metal leaching	Mill reagents
Control of reactions			
• Conditioning of tailings/removal of sulphides	Yes	Yes	
Covers and seals for exclusion of water	Yes	Yes	
• Covers and seals for exclusion of oxygen	Yes		
• Application of alkaline additives	Yes		
• Bactericides	Yes		
• Add fixing/neutralising agents in the mill process	Yes		Yes
Control of migration			
• Covers and seals to reduce infiltration	Yes	Yes	Yes
• Diversion of surface water	Yes	Yes	Yes
• Interception of groundwater	Yes	Yes	Yes
Collection and treatment			
• Active treatment in chemical treatment plant	Yes	Yes	Yes
• Passive treatment using wetland	Yes	Yes	Yes
• Passive treatment using alkaline trench	Yes		
• Passive treatment using retention pond			Yes

3.2 Covers

The objectives of a cover system may vary from site to site but generally include:

- Dust and erosion control
- Chemical stabilisation of potentially acid generating tailings (through control of oxygen ingress and/ or water infiltration)
- Control of contaminants release (through control of infiltration)
- Provision of a growth medium for establishment of vegetation

Thus on the basis of their design objectives, the various types of tailings covers can be classified in three categories, (MiMi 1998, Ritchie 1999, DeVos et al. 1999):

- ***Oxygen barrier covers*** that limit the transport of oxygen into the tailings either by acting as a barrier against oxygen diffusion (*water cover*) or by consumption of oxygen, which penetrates into the cover, thereby controlling the rate of sulphides oxidation.
- ***Low water flux covers*** that aim to inhibit infiltration to the waste. Covers of this type include the *low permeability cover* (water-shedding cover), the *capillary barrier* and the *evapotranspiration* cover.
- ***After use cover*** that aims to improve the appearance of tailings surface, to prevent surface erosion, to limit contact between the tailings and the surface runoff and to provide a growth medium for establishment of sustainable vegetation.

Cover design is site specific depending on the tailings characteristics, climatic conditions, material availability and the sensitivity of the receiving environment. A methodology for selecting a cover design for unsaturated acid generating tailings is shown in Figure 1.

A water cover is often the method of choice for reclaiming tailings, which are potentially acid generating. The tailings voids remain permanently water-filled and thus unavailable to oxygen, while a water depth of two to three meters sufficiently reduces dissolved oxygen at the submerged tailings surface. Both laboratory and field demonstrations, notably from the Canadian MEND program, have shown submergence to be virtually 100 percent effective from a geochemical point of view.

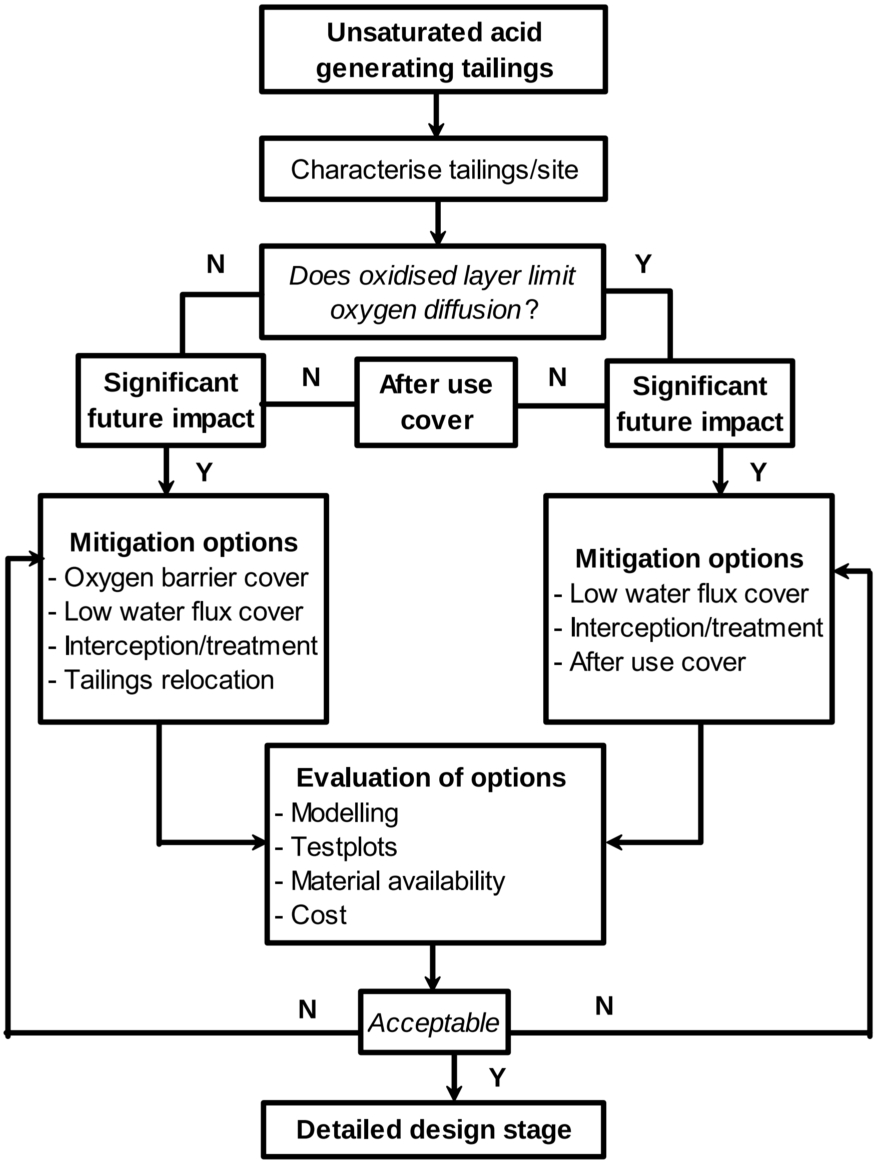


Figure 1: Flow sheet for cover selection (after DeVos et al. 1999).

However, a water cover is not suitable if (Wels et al. 2000):

(i) a water cover would result in too much contaminated seepage;
(ii) the embankments would not be stable and/or could not be economically stabilized; and
(iii) the water balance for the cover pond would be such that the water cover could not be sustained.

Under any of the above circumstances, a dry cover represents the method of choice for reclamation of the tailings. The design of a dry cover can vary widely ranging from a single soil layer to promote revegetation to a complex (multi-layer) cover to reduce ingress of oxidation and/or infiltration.

The processes applied in the closure of storage facilities involving different types of tailings are summarised in Table 8.

Table 8: Summary of applied processes in the management of tailings (modified from BREF 2004).

Mineral	Chemistry/ Mineralogy	Mineral processing	Tailings characteristics	Tailings management	Closure and after care
Base metals	Mostly sulphides	Flotation	Often potentially acid generating	Slurried, sub-aqueous discharge backfill (coarse fraction)	Wet cover or dewater & dry cover
Bauxite	Al_2O_3, SiO_2, Fe_2O_3, CaO, TiO_2	Bayer process	Elevated pH, salinity	Slurried or thickened	Dewater and dry cover, discharge treatment
Coal	Carbon, ash, sulphur	Coarse fractions in jigs/ dense medium, flotation for fines	Clay, shale, sandstone, sulphides, can be radioactive	Coarse tailings on heaps/ old pits, fines in ponds, sort or filtered and to heaps	Dewater and dry cover
Phosphate	Apatite, phlogopite mica, carbonates, silicates	Flotation	Fine particles and slimes (-0.1 mm) mainly contain clay creating settling problems	Slurries in ponds	Dewater and dry cover
Precious metals	Complex sulphides, native gold	CN leach, spirals, shaking table	Some potentially acid generating, in case of CN leach, contain cyanide, complexed metals, thiocyanate	Slurried, backfill (coarse fraction), CN destruction	Wet cover or dewater & dry cover raised ground water table
Uranium	Uranium oxides, carbonates, silicates, sulphides	Conventional mill process, heap or in situ leaching	Radioactivity, some potentially acid generating	Slurried, sub-aqueous discharge	Wet cover or dewater & dry cover

3.2.1 Water covers

A water cover, or 'wet cover', is a closure method, which uses free water as an oxygen diffusion barrier. The oxygen diffusion coefficient is 10^4 times less in water than in air. This implies that if a water cover can be established, sulphide oxidation can be almost eliminated. The prerequisites for a water cover are (BREF 2004):

- a positive water balance, which can guarantee a minimum water depth at all times
- long-term physically stable dams
- long-term stable outlets with sufficient discharge capacity even during extreme events
- a water depth within the pond deep enough to avoid the re-suspension of tailings by wave action (break waters can be used to reduce the required water depth)
- that the tailings can dissolve in water.

Furthermore, it is a benefit if there is a natural stream entering the pond, i.e. one which can supply organic material, flora and fauna to the decommissioned system. This will further improve the performance of the water cover by providing an additional diffusion barrier due to the sediments and can speed-up the re-colonisation of the system. Water covers are a closure option for tailings ponds of any type (e.g. for 'normal' tailings discharge or for subaqueous discharge during operation).

MEND (Tremblay 2000) have prepared and developed a generic design guide for water covers and they outline the basic guidelines and direction on where and how to apply this method of tailings disposal (MEND 2.11.9). The guide outlines the factors involved in achieving physically stable sediments, and discusses the chemical parameters and constraints that need to be considered in the design of both impoundments, and operating and closure plans. The idea of maintaining wastes saturated in water will require monitoring of the ground and surface water levels in perpetuity and this will still entail significant costs.

The performance of *in situ,* shallow water covers in controlling acid generation was evaluated at four recently decommissioned pyritic uranium tailings sites at Elliot Lake, Ontario, Canada (Ludgate et al. 2003). The tailings are acid generating, having a pyrite content of approximately five to ten per cent and a very low to non-existent alkaline buffering capacity. Adverse market conditions led to the closure of all operating uranium mines in the early- to mid-1990s, followed by rehabilitation and decommissioning of mine and waste management facilities. In order to control acidic drainage, all new and active tailings areas at Denison, Quirke (Figure 2), Panel, Spanish-American and Stanleigh mine sites were re-engineered to provide *in situ* submersion of these tailings under shallow water covers. Specifically, the evaluation of potential options, including direct vegetation, soil covers and tailings relocation for closure of the tailings basins of Denison mines, i.e. the largest uranium mine in the Elliot Lake region, Canada concluded that a water cover would control acid generation, eliminate dusting, reduce radiation exposure (lower gamma fields and radon releases) and would restore the lands to a condition similar to that which existed prior to mining (lakes and wetlands) (Laliberte et al. 2003). The tailings impoundment dams were upgraded and reinforced or in some cases reconstructed, to minimise seepages and provide a minimum 1 m depth of water cover. The water covers at these sites being in operation for a period of 6-9 years have been performing as designed and acid generation has been reduced to low levels. Based on the total amount of yearly equivalent limestone required to maintain water quality in the water cover and at the effluent treatment plant, it is concluded that acid generation rate at the Denison tailings facility has reduced to less than 0.15 per cent of its pre-water cover conditions during normal operation and rehabilitation periods. The acid generation rates at Denison and Panel tailings areas have decreased to less than 1.6 per cent of that at the Nordic tailings facility, which was revegetated during the late-1970s. Furthermore, the water covered Denison TMFs are becoming productive wetland areas with the invasion of many plants and animals.

Figure 2: Water cover implemented at Quirke tailings facility, Elliot Lake, Ontario, Canada.

Two examples of European sites where water covers have been implemented are Stekenjokk and Kristineberg, Sweden. Stekenjokk constitutes a pioneer site set up for the decommissioning of tailings ponds containing sulphide tailings. The decommissioning occurred in 1991, which therefore provides for more than ten years of evaluation of the results. The implemented measures at Stekenjokk are schematically shown in Figure 3.

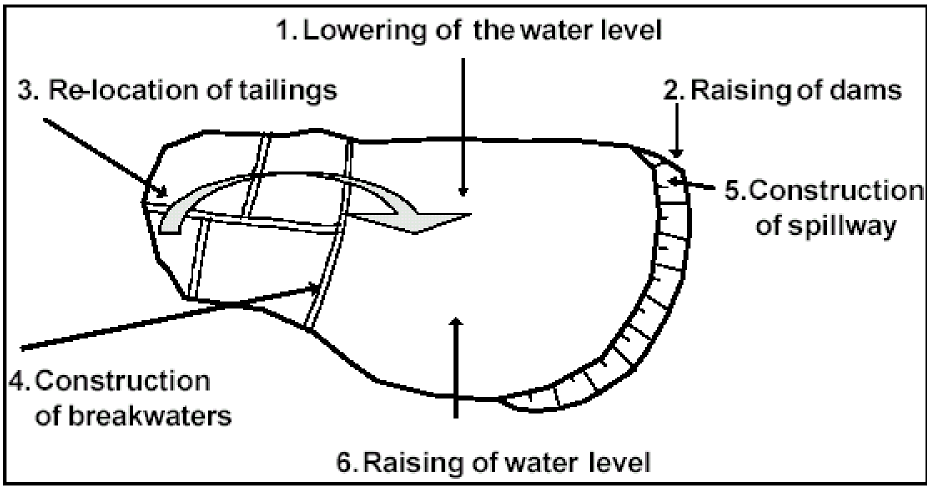


Figure 3: Implemented measures at Stekenjokk TMF (Broman and Göransson 1994).

Monitoring results have indicated that the water cover efficiently reduces the sulphide oxidation rate of the deposited tailings. Expressed as the oxygen flux through the water cover to the tailings, the upper limit of the sulphate outflow of the pond corresponds to an upper limit of the effective oxygen flux of 1×10^{-10} kg O_2/m^2s. This is comparative to, or even better than, that obtained from engineered composite dry cover solutions. The implemented water covers had an investment cost of USD $2/m^2$ compared to the costs of studied dry covers of USD $12/m^2$. Furthermore, no borrow pits needed to be opened for the extraction of cover material.

Some additional information has been gained by studying natural lakes that have been used for the subaqueous deposition of tailings for relatively long time periods. Fraser and Robertson (1994) reported that tailings sub-aqueously deposited in Mandy Lake between 1943 and 1945 show little or no evidence of chemical reaction after 46 years on the lake floor. There are also studies showing similar results for Buttle Lake (Vancouver Island).

3.2.2 Dry covers

Final dry cover systems of waste disposal facilities are composed of multiple layers, which can be grouped into five categories as given in Table 9 (Rumer and Mitchell 1996).

Undoubtedly, not all layers are needed for all types of covers. The design criteria are based on a number of site-specific factors including:

- Climatic conditions of the site
- Geomechanical/ geochemical properties and environmental risks of the disposal area
- Borrow material type and availability
- Closure strategy and
- Cost.

Table 9: Layers of the final cover at the waste disposal sites (Rumer and Mitchell 1996).

a/a	Layer	Primary functions	Potential materials	Factors affecting performance
1	Surface layer	• Separation of underlying layers from the ground surface. • Resistance to wind and water erosion. • Protection of underlying layers from temperature and moisture extremes.	-Topsoil vegetated -Geosynthetic layer over topsoil -Cobbles -Paving material	Erosion, evapotranspiration, vegetation
2	Protection layer	• Storage of infiltrated water until its removal by evapo-transpiration. • Separation of waste from humans, burrowing animals and plant roots. • Protection of underlying layers from wet-dry and freeze-thaw cycles, which may cause cracking.	-Soil -Cobbles -Recycled or reused waste (e.g. fly ash, bottom ash and paper mill sludge)	Erosion, slope failure due to pore pressure buildup, animal burrows
3	Drainage layer	• Reduction of water head on the barrier layer. • Reduction of pore water pressures in the overlying layers, thus increasing slope stability. • Reduction of the time during which the overlying layers are saturated following rainfall events, thereby decreasing erosion.	-Sand or gravel -Geonet or geo-composite -Recycled or reused waste	Clogging, insufficient capacity and drainage outlets
4	Hydraulic and/ or oxygen* barrier layer	• Inhibition of water percolation and/ or • Prevent oxygen diffusion	-Compacted clay -Geomembrane -Geosynthetic clay liner -Recycled waste -Asphalt -Capillary barrier	Cracking due to desiccation, de-formation from settlement or seismic action, root penetration, stability
5	Foundation layer	• Foundation for the cover	-Sand or gravel -Soil -Waste	Adequate strength

**applicable to sulphidic wastes with acid generation potential*

A low water flux cover, containing a low permeability layer, has been commonly applied for covering the waste disposal areas in compliance with regulations on the landfill of waste. In Europe, recent regulations on the landfill of waste (Council Directive 1999/31/EC) recommend that the final cover consists of a low permeability layer (k: 10^{-9} m/sec) of thickness 1 m (non hazardous wastes) or 5 m (hazardous wastes), shown in Figure 4.

Where the geological barrier does not naturally meet the above conditions it can be completed artificially and reinforced by other means giving equivalent protection. An artificially established geological barrier should be no less than 0.5 m thick.

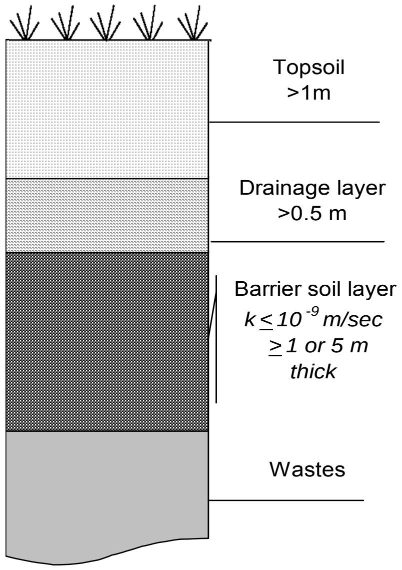


Figure 4: Surface barrier for waste disposal areas in compliance with the European legislation on the landfill of waste (1999/31/EC).

Covers with low permeability layers

The barrier - low permeability layer - is considered the most critical engineered component of this type of cover systems. The theory and practice of barrier layers is broadly applicable, regardless of waste type. Conventional artificial barriers developed, applied as single liners or combinations (composite barriers) include (Daniel 1993):

- Compacted clay layer
- Flexible membrane liners and
- Geosynthetic Clay Liners

Historically, a <u>compacted clay liner</u> has been the most commonly used barrier layer. For sites where the available soil does not contain enough clay to be capable of being compacted to the desired low hydraulic conductivity, commercially clay minerals, such as sodium bentonite, may be mixed with the soil. A number of physical/geotechnical parameters control the engineering properties of soil barriers including the grain size distribution, Atterberg limits, water content and energy of compaction and bonding of lifts (EPA/625/4-91/025).

The main problems associated with the compacted clay liners include damage due to desiccation during the dry period and differential settlement. In-place costs of a single compacted clay liner typically vary from 3 to 25 € per square meter depending on thickness, availability, size and type of facility. Under extreme conditions (e.g. lack of clay locally), the cost could be much higher (Daniel 1993).

<u>Polymeric geomembranes or flexible membrane liners (FMLs)</u> are usually made of continuous polymeric sheets that are flexible. Polyethylene (PE) is probably the most common synthetic lining material, either as High Density Polyethylene (HDPE) or less commonly low density polyethylene (LDPE) whereas polyvinyl chloride (PVC) may also be used. They typically range in thickness from 0.06 to 0.24 cm and come in sheets and rolls of various sizes. Critical parameters in the design of a geomembrane in a landfill cover include liner compatibility, vapour transmission, biaxal stresses via subsidence and planar stresses mobilised by friction (EPA/625/4-91/025).

Durability and aging of geomembranes have to be taken into account, when the long-term performance of the cover in the postclosure period is assessed. Degradation processes such as ultraviolet radiation are prevented by burying the geomembrane in soil soon after installation. However, long-term oxidation of geomembranes is a degradation mechanism that can only be retarded, via anti-oxidants, but not eliminated (EPA/625/4-91/025). Based on recent studies, depletion of antioxidants from HDPE geomembrane may take from 45 to 115 years and the geomembrane service life may be about 250 to 900 years, depending on the specific product and in-place conditions.

The range of installed costs for the geomembranes typically used in cover systems is relatively narrow in comparison to the other liner materials. For geomembranes with good out-of plane deformation properties and a thickness of approximately 1 mm, the installed cost amounts to 5-9 € /m^2 (Daniel 1993, Adam and Mylona 2001).

A relatively new technology (developed in 1986) gaining acceptance as a barrier system in solid waste landfill applications involves the Geosynthetic clay liners (GCLs). These are factory-manufactured hydraulic barriers consisting of a thin layer of bentonite (~ 5.0 kg/m^2) sandwiched between two geotextiles or bonded to a geomembrane (US EPA 530-F-97-002). The structural integrity of GCLs is maintained by stitching or needle-punching, and/ or binding the geotextile or geomembrane to the bentonite by adding an adhesive to the bentonite. GCL technology can provide barrier systems with very low hydraulic conductivity, in the range of 10^{-11} to 10^{-12} m/sec, performing at or above standard European and international performance levels. Some of GCL brands currently available include Bentofix®, Bentomat®, Clay max®, Gudseal® and NaBento®. The primary differences between GCLs include the mineralogy and form of bentonite (e.g. woven vs. non-woven geotextiles), the addition of a geomembrane and the bonding methods. The bentonite thickness of GCLs varies between 7 and 10 mm.

Based on the review and evaluation of alternative covers by Rumer and Mitchell (1996), a final cover incorporating a GCL barrier layer can outperform that with a compacted clay layer. While a clay layer will frequently crack due to differential settlement, wetting-drying and freezing-thawing cycles, a GCL has the ability to self-repair any rips or holes caused when subjected to these stresses due to the swelling properties of bentonite. One of the primary concerns with using GCLs in covers is the low shear strength at mid-plane. Furthermore, this technology requires additional field and laboratory testing to further assess its effectiveness as a landfill barrier system in terms of key performance standards including hydraulic conductivity, bearing capacity, slope stability, long-term reliability and resistance under freeze-thaw cycles. The cost of an installed GCL amounts up to 11.5 €/m^2 (GSI 2000).

Composite covers, include the geomembrane/compacted clay liner, which is recommended by U.S Environmental Protection Agency (U.S EPA/625/4-91/025) for the covering of hazardous waste disposal facilities, the geomembrane/GCL liner, and very conservative options like the geomembrane/compacted clay/geomembrane and the geomembrane/ GCL/geomembrane liners. Based on the study of Kim and Benson (1999), multilayer caps containing a composite geomembrane/GCL or compacted clay barrier can be also very effective at limiting oxygen transport into sulphidic mine wastes, inhibiting acid generation. The geomembrane was considered as a key component in impeding oxygen diffusion.

The cost of composite covers is estimated to be the sum of costs accounted for each component of the cover system. Thus, the cost of a composite cover consisting of a geomembrane in intimate contact with a compacted clay liner will average 17 € /m^2.

Capillary barrier

An alternative appealing technique for the sealing of waste disposal facilities relies on the use of natural soils to generate a capillary barrier system where a fine grained soil layer overlays a coarse grained soil (Figure 5). At most water contents, except near saturation, fine-grained soils have higher matrix suctions than coarse grained soils due to their different soil-water characteristic curves. As a result, the apparent hydraulic gradient in a capillary barrier near the fine-grained/coarse-grained interface is normally upward, except when the upper layer becomes nearly saturated. In addition, infiltrated water is stored in the fine-grained layer until the matrix suction becomes low enough to permit water entry in the coarse-grained layer.

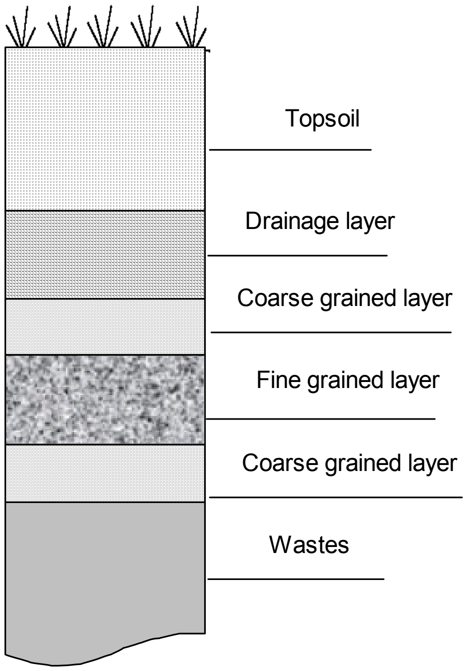


Figure 5: Cross-section of a capillary barrier system.

Because coarse-grained soils have very low unsaturated hydraulic conductivities at low water content, the coarse-grained layer impedes flow. These factors constitute the "capillary barrier effect" which inhibits water infiltration (Khire et al. 1996). Water stored in the fine grained layer due to the capillary barrier effect may be diverted in a horizontal direction away from the underlying waste layers (applicable at humid sites) or removed via evapotranspiration (semi-arid and arid sites). A similar effect can be created when a coarse material is placed over a fine material, shown in Figure 5. Such configuration prevents water rising by capillary force, from the fine to the coarse material. In this typical layered cover system, the upper and lower coarse-grained layers inhibit the flow of water from the fine material layer and help maintain a high degree of saturation. Given that oxygen diffusion is low in water saturated soils, capillary barriers could also perform as a barrier against oxygen transport from the atmosphere into the sulphidic wastes, preventing their oxidation and subsequent acid generation (Nicholson et al. 1989).

For the design of a capillary barrier cover, detailed characterization of the construction materials, including grain size distribution, hydraulic conductivity, soil-water characteristic curve and careful consideration of the site water balance and the geometry of the deposit is required.

Other types

Covers recently designed for application at sites with dry climate, i.e. where annual precipitation is low, i.e. less than 300 mm/year and potential evapotranspiration is high, i.e. 700 mm/year include the Anisotropic Barrier and the Evapotranspiration Cover. The design of Anisotropic Barrier aims to limit downward movement of water while encouraging lateral movement. This cover is composed of a sequence of capillary barriers, as shown in Figure 6 (a). Finally, the Evapotranspiration Cover is a soil cover with an engineered vegetative cover, Figure 6 (b).

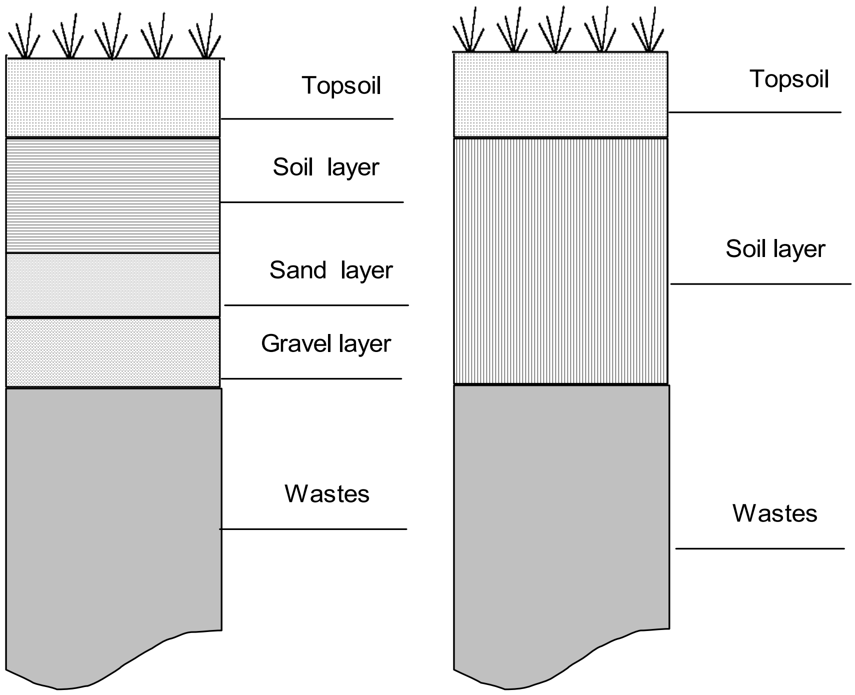


Figure 6: Alternative soil covers developed for sites with dry climate (a) Anisotropic Barrier and (b) Evapotranspiration Cover.

Such a cover stores infiltrating water in the root zone long enough to allow evapotranspiration to remove it before its downward migration into the waste (Swanson et al. 1997). The performance of such covers is currently tested in field scale within the Alternative Landfill Cover Demonstration, ALCD (www.sandia.gov) and the Alternative Cap Assessment Project, ACAP (www.dri.edu/Projects/EPA/boston-brochure2.html). More specifically, the water balance of twenty-one landfill final cover test sections has been evaluated as part of the United States Environmental Protection Agency's Alternative Cover Assessment Program. Based on data from the test sections, the alternative covers in arid and semi-arid climates generally are transmitting significantly less percolation than the alternative covers in humid climates (Roesler et al. 2002). Percolation rates for the alternative covers in arid and semi-arid climates typically are less than 1 mm/yr. For the humid sites, percolation typically is between 37 and 144 mm/yr, however it should decrease over time as the vegetation matures, and is capable of removing more soil water. Data from the test sections simulating a composite cover (i.e., a geosynthetic clay liner or compacted clay barrier overlain by a geomembrane) indicate that these covers are very effective when constructed properly. Percolation rates for the composite covers are generally less than 1 mm/yr in semi-arid and arid regions, and 5 mm/yr in humid regions. Data from the test sections simulating compacted clay covers show that clay barriers are highly susceptible to desiccation cracking and can transmit percolation at large rates (several hundred mm/yr). Protection of geomembrane is also a key factor. Methods or materials that damage the geomembrane during construction will lead to higher than anticipated percolation rates.

A large amount of research into the design of dry covers for uranium mill tailings was conducted under the US Uranium Mill Tailings Remediation Action Program (UMTRA) in the 1980s. Based on the regulations promulgated by the Environmental Protection Agency (EPA: 40 CFR 192) and the Nuclear Regulatory Commission (NRC: 10 CFR 40), the uranium tailings pile must have a cover designed to control radiological hazards for 1,000 years, to the extent reasonably achievable, and in any case, for at least 200 years. It must also limit radon (^{222}Rn) releases to 20 picocuries per square meter per second (20 $pCi/m^2/s$) averaged over the disposal area (Robinson 2004). An example of cap designed by UMTRA is shown in Figure 7. The cap incorporates a 0.5 m thick layer of highly compacted silty clay soil, partially amended with bentonite, having a low permeability, i.e. k: $<10^{-9}$ m/sec, overlain by layers for protecting the radon barrier against erosion, frost, and infiltration.

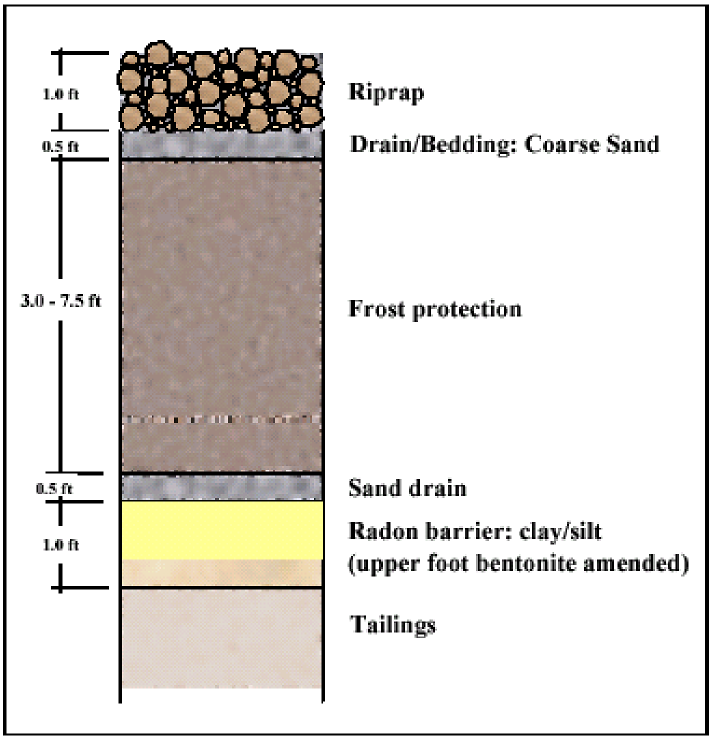


Figure 7: Cover design for the UMTRA Estes Gulch containment structure, Colorado (IAEA 2004).

The cross-section of a multi-layer cover design combining fundamental ecological principles with engineered barriers is shown in Figure 8. The capillary barrier under a thick soil 'sponge' mimics the natural soil profile, in which thick loess stores precipitation that is eventually lost through evapotranspiration, thus maintaining unsaturated conditions in the subsoil. The cover is also designed to control radon flux, biointrusion and erosion, and to protect critical interfaces from frost. Studies of natural analogues suggest that the cover performance is likely to improve over the 1000-year design life.

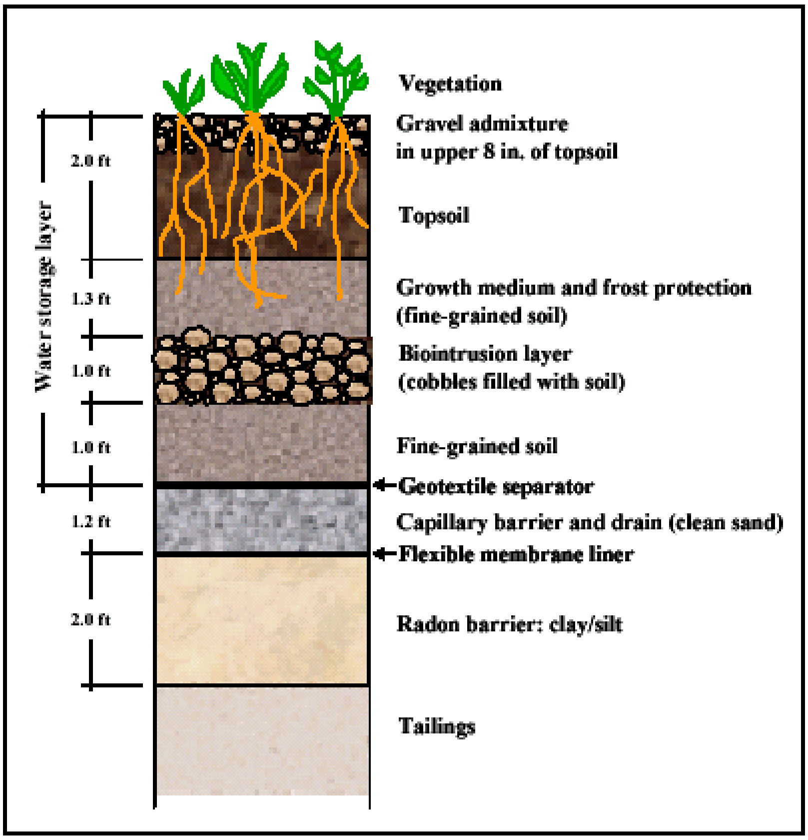


Figure 8: Cover design for the UMTRA Monticello containment structure, Utah (IAEA 2004).

A multibarrier dry cover (i.e. 0.5 m thick layer of rolled soil/loam/clay, 1 m of waste rock and vegetation layer) was applied for the rehabilitation of the uranium tailings storage facility (7.1 Mt of uranium tailings) of Mary Kathleen mine, Northwest Queensland, Australia in the mid-1980s. At the time of mine closure, it was predicted that acid mine drainage generation would not eventuate and that uranium, heavy metals and radionuclides would be adsorbed within the tailings and not seep from the tailings facility into the environment. Current studies of the rehabilitated tailings area have revealed that the dry cover has no signs of erosion and radiation levels are within acceptable limits. However, the flow rate of surface seepage occurs at a much higher rate than predicted. Furthermore, acid drainage has developed resulting in the mobilisation of metals, radionuclides and sulphates (Lottermoser et al. 2003).

An example of successful application of dry cover in Europe for the remediation of uranium tailings is the Ranstad tailings facility (25 ha, 1 Mm^3 of uranium tailings) in Sweden (Sundblad 2003). The cover aiming at the reduction of water infiltration and oxygen diffusion into the tailings incorporated a low permeability ($k < 5 \times 10^{-9}$ m/sec) moraine layer in compliance with the regulations. The cover also included a limestone layer to act as a drainage layer, overlain by a protective layer of moraine and topsoil (Figure 9).

The cover system was completed in 1992 and ten years later it was concluded that the cover still works as planned. The infiltration through the sealing layer was estimated to 10% of the precipitation and the oxygen content below the sealing layer was about 5 % of the oxygen content in the free air. Seepage is at present being contained and treated, but seepage quality has already improved (a reduction in the concentration of radioactive elements and heavy metals in the order of 75 to 85 % was observed) and it is hoped that water treatment and further maintenance can soon be abandoned. The total reclamation costs are estimated at US$ 25 million.

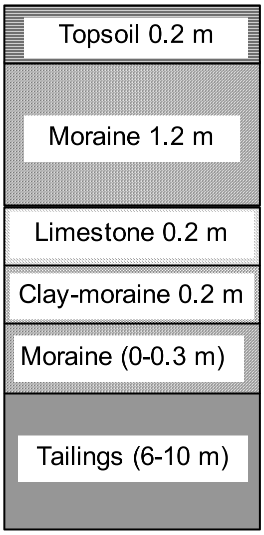


Figure 9: The final cover system of tailings facility at the Ranstad site, Sweden.

The cost associated with large scale mining applications is considered the limiting factor for the extensive use of the various materials proposed as mining covers. Although both natural and synthetic covers may be cost-effective when applied in relatively small disposal areas, they may not be feasible for the large tailings disposal facilities, typical in the mining industry. Thus, further research studies were performed for the potential use of other readily available, inexpensive and potentially non-phytotoxic, non-polluting waste products including depyritized tailings, granulated slags, paper mill sludge and fly ash.

Waste rock has been used for covering the tailings dam of Junction Reefs Gold Project, New South Wales, Australia (Figure 10). A layer of hard rock waste placed on the tailings would provide a capillary break preventing salts rising to the overlying oxidised waste and/or soil layers. Highly oxidised waste (overburden) was also preferentially used instead of topsoil as the oxidised waste has similar chemical and physical properties to the topsoil but without organic carbon and seeds of weedy species.

(a) (b)

Figure 10: View of tailings dam of Junction Reefs Gold Project, New South Wales, Australia. (a) During rehabilitation workings, involving covering with layers of hard rock waste and oxidised waste, fertilising and sowing with pasture. (b) After rehabilitation (Environment Australia 2002).

For potentially acid generating sulphidic wastes, organic oxygen consuming materials like peat, lime stabilized sewage sludge and municipal solid waste compost have also been used (MiMi 1998). Use of waste products is not only considered economical, but it also eliminates the need for the safe environmental storage of such materials. However, these wastes often contain potentially toxic substances, which may inhibit plant growth or eventually leach into the surrounding environment.

Stabilisation of tailings for the placement of dry cover

The design and construction of soil covers on tailings often presents a formidable challenge due to the low shear strength, poor trafficability, and high settlement of underconsolidated tailings at the time of reclamation.

A review of dry cover placement on extremely weak, compressible tailings was presented by Wels et al. (2000). It was concluded that the optimal technique (or combination of techniques) for placing a dry cover will vary from site to site and is influenced by the environmental and geotechnical circumstances as well as cost and availability of materials and equipment used for cover placement. The geotechnical issues to be considered include:

- consolidation of near-surface tailings to achieve strength gains, improve trafficability, and allow safe placement of initial cover layer;
- stability of tailings slopes during dewatering of tailings ponds and/or cover placement; and
- long-term settlement of tailings and its impact on cover integrity and final surface shaping.

The environmental issues to be considered include:

- management of contaminated (free) pond water;
- management of contaminated pore water expelled during tailings consolidation; and
- management of (uncontaminated) surface water on top of the cover.

Based on the experience gained by a large uranium tailings reclamation project (Helmsdorf tailings impoundment, Germany) a good understanding of the geotechnical properties of the slimes is essential for selecting the most suitable strategy for cover placement. The combined use of consolidation and slope stability modeling was found to be a powerful tool for initial selection of cover placement equipment and cover advance rates. Field tests and field trials were performed to confirm initial modeling results and to finalize the cover placement design.

In addition to material characteristics, data and information describing the preconstructional topography, embankment details, the thickness of the deposit, the tailings discharge/deposition history, and the drainage conditions at the tailings pond base should be evaluated during remedial preparation and planning (Jakubick et al. 2003).

Natural processes of consolidation may take tens of years before pore pressures dissipate and settlement ceases. Thus reclamation profiles must either allow for such long-term consolidation or the process must be accelerated. Numerous techniques have been developed to allow access onto the surface of weak unconsolidated tailings. The most widely used approach is to allow drying to form a “crust” of desiccation strengthened tailings, reinforce this with synthetic geogrid, and then advance thin layers of cover fill using light equipment. An example of extensive covers placed by such techniques is the covering of the WISMUT tailings ponds in Germany. High permeability drainage elements, most commonly in the form of band drains, may be also placed into the upper layers of the slimes. The band drains reduce the effective drainage path length (from the total tailings depth to half the horizontal spacing of the drains) significantly accelerating the consolidation process and allowing earlier access and faster advance rates during actual cover placement.

The “dry” tailings reclamation strategy followed at WISMUT involves the following steps:

(1) Decanting of the “free” pond water
(2) Placement of an interim cover on the tailings surface to provide the consolidation load an create a stable working platform;
(3) Building of a stable surface contour providing suitable run off conditions for the surface water;
(4) Capping of the surface with a final cover.

Each remedial step leads to a disturbance of the geomechanical balance, which then has to be allowed to re-establish before taking the next step. The general direction of remediation is from the sandy beach zones toward the slimy central parts of the impoundment. Advancing over slimes of lower shear strengths (< 5 kPa) requires thinner initial cover layers and use of lighter equipment and/or use of long arm hydraulic shovels. A subaquatic placement of the initial cover layer onto slimes is used at the Helmsdorf site of WISMUT. The approach is rather complex but has the advantage that the total weight of the initial layer can be applied to the slimes in small increments with no construction equipment load. Sand cover placement with hydraulic means has also been successfully used at the Syncrude tailings facilities in Alberta, Canada. The remediation methods used for various tailings types/zones (as summarized for Syncrude) are presented in Figure 11.

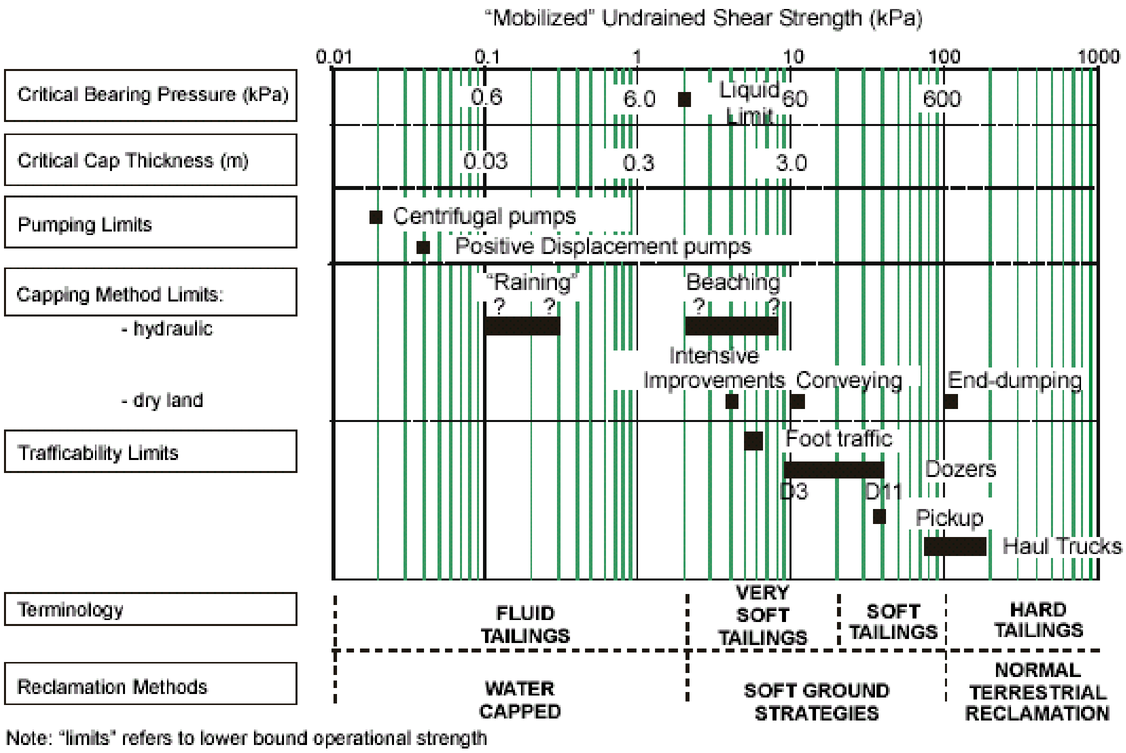


Figure 11: Remediation methods as a function of tailings shear strength and critical parameters (Jakubick et al. 2003).

A very important part of the construction of the interim cover is the vigilant observation of the tailings response to cover placement and the flexible adjustment of the advancement and technology to the changing field conditions and changing material properties.

3.2.3 Oxygen consuming cover

Municipal Solid Waste (MSW) and other organic based materials could be used as an oxygen barrier cover for tailings. The compost layer would function as both a physical barrier and as an oxygen-consuming layer that would permanently prevent sulphide oxidation and the resultant AMD. The organic layer on sulphide tailings can be beneficial in five ways:

1. *Physical oxygen barrier* - the compost would be saturated with water over at least part of its depth so that the limiting factor in oxygen diffusion would be the diffusivity of oxygen in water;
2. *Oxygen-consuming barrier* - the continued decomposition of compost creates a large biological oxygen demand that acts as a sink for diffusion of atmospheric oxygen or dissolved oxygen;
3. *Chemical inhibition* - compounds and decomposition products in the MSW compost that leach into the tailings inhibit the growth and metabolism of sulphate-producing bacteria;
4. *Chemical amelioration* - organic constituents in the MSW compost can cause the reductive dissolution of ferric oxides and prevent indirect ferric sulphide oxidation and acid generation; and
5. *Reduced water infiltration* - reduced hydraulic conductivity of compacted compost may prevent infiltration of precipitation, thus decreasing tailings groundwater flow.

At the East Sullivan massive sulphide mine in Quebec, a 2 m thick cover of wood wastes are placed over acid generating tailings and this effectively prevents oxygen from reaching the tailings. Tasse et al. (1997) showed that the waste cover at this site can lead to full anaerobic conditions, with methanogenesis. The decomposition of the barrier results in an increase in the alkalinity of the ground water and constitutes a large reservoir of organic compounds, which drives redox reactions. Thus the barrier is working as an oxygen barrier as well as a system, which increases the alkalinity and lowers the redox. Waste wood covers are in use on about 85% of the 30-year-old sulphidic acid-generating tailings at East Sullivan. Pore gases were analysed in several wood piles, of both deciduous and coniferous trees, in order to understand the factors which control wood degradation and so determine the effective life span of such an organic waste cover (Figure 12).

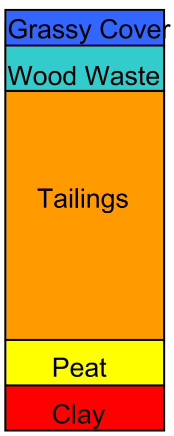


Figure 12: Idealised section showing reclamation concept of East Sullivan tailings pond.

Long-term efficiency seems to depend on the degree of water saturation at the bottom of the pile, probably because of the build-up of a microbial mass in such an anaerobic environment. The addition of nutrients would promote composting and create a more functional and longer-lasting barrier (Tasse 2000). At mine sites in the USA coarse woody debris is now being incorporated into tailings with the addition of up to 7 tons per acre to provide a substrate for essential micro-organisms.

A cover with a high content of organic material was constructed at Galgbergsmagasinet tailings pond in Falun, Sweden (BREF 2004). The tailings surface was covered with a 1 m thick layer of fly ash mixed with paper mill sludge overlain by a 0.5 m layer of wood waste and coarse till. This cover is believed to form an effective barrier against oxygen transport partly due to consumption of oxygen in the cover and partly due to a physical barrier effect in the compacted low permeable mixture of fly ash and paper mill sludge. The hydraulic conductivity of the mixture was measured in the laboratory at 5×10^{-9} m/s and the water retention capacity was measured and considered satisfactory to maintain a high degree of saturation in the barrier. Other possible positive effects are inhibiting of the acidophilic leaching bacteria due to the high content of calcium hydroxide in the fly ash that will raise the pH in the percolating water, and the formation of a sustainable environment for sulphate-reducing bacteria producing hydrogen sulphide that precipitates metals. However, there is also a risk that the combination of organic compounds and iron hydroxides in the upper (oxidised) part of the deposit could produce bacterial iron reduction that would dissolve co-precipitated heavy metals. Monitoring results indicate that the oxidation of sulphides has decreased and pH at the site is higher than at the reference site. No evidence of any significant bacterial sulphate reduction has yet been noticed.

3.2.4 Wetlands

Wetlands are defined as having (Mitch and Gosselink 1986):

(1) a water table above or at the soil surface for a significant proportion of the year, which is a determining factor in their make-up of the ecosystem,
(2) an emergent vegetation characteristic of wet biotopes (often containing a large proportion of helophytes), and
(3) a soil characteristic of wet biotopes (anoxic, chemically reduced).

Wetland establishment as a closure method uses the same principle as the water cover but with less water depth as the plant cover stabilises the bottom thereby avoiding the re-suspension of tailings. Less water in the pond reduces the potential risk for a dam failure. The prerequisites are the same as for water covers but with the additional requirement of adding organic matter, to enhance the establishment of the wetland vegetation in the pond. It should be noted that the principal idea of a wetland establishment is not the treatment of the water but the establishment of a self generating and sustainable cover that reduces the requirements for the water depth and that acts as an oxygen consuming barrier when organic matter is deposited on top of the water saturated tailings.

Wetlands are attractive as an endpoint in the rehabilitation of mine wastes, such as tailings and tailings water, for two reasons. First, pollutants originating from mining activities, such as metals and sulphur, are relatively immobile when present under waterlogged conditions. Second, pollutants are retained by the wetlands from water passing through the wetlands. Both characteristics are largely due to the same processes. Permanently waterlogged wetland soils are generally anaerobic, because of the relatively low diffusion rate of oxygen through water compared to air. In addition, micro-organisms present in such soils respire using terminal electron acceptors other than oxygen. Such organisms can, for example, reduce ferric iron to its ferrous form, or reduce sulphate to sulphide. Co-precipitation of metals, including iron, zinc, lead and cadmium can also occur (Sullivan et al. 1999).

Several UK coal TMFs have been restored as wetlands. Examples of sites where wetlands are considered/ planned to be implemented are Lisheen and Kristineberg in Sweden.

The Lisheen orebody is the largest of its kind to have been discovered in Northern Europe in the last ten years. Upon closure it will have generated 6.63 million tonnes of pyritic tailings which will be deposited in a TMF with a final surface area of approximately 64 ha and embankment walls 15.5m high. The mine rehabilitation plan for Lisheen calls for the deposition of layers of organic-enriched crushed limestone over the tailings that will then be handplanted with reed rhizomes and other wetland vegetation (Treacy and Timpson 1999). The core intent of this plan is that the limestone layer, water cover and organic matter produced by the vegetation will inhibit excessive pyrite oxidation in the tailings and prevent the generation of AMD. Ultimately the plan aims to have the TMF remain as a landscaped artificial dam containing an ecologically-sustainable reed marsh similar to the margins of many Irish calcareous marl-based lakes. The Lisheen closure plan also proposes to construct secondary wetlands to treat any overflow from the TMF.

3.2.5 Revegetation

Revegetation is an essential part of rehabilitation process. A vegetation cover on mine tailings can be effective in controlling surface erosion, providing the necessary surface stability to prevent wind-blow of tailings particles, reducing infiltration by interception of rainfall and improving aesthetics (Ritcey 1989). However, physical and chemical characteristics of mine tailings are often inimical to successful vegetation establishment. Plant growth on tailings is significantly inhibited by limitations including residual high levels of heavy metals, excess salinity and acidity, macronutrient deficiencies and poor physical structure (Ernst 1988). Such features result in most metal wastes being largely devoid of any natural vegetation, even many years after abandonment.

Current approaches to revegetation of mine wastes include agricultural, adaptive and ameliorative strategies (Johnson et al. 1994). The agricultural approach involves direct seeding with commercially available or native plants and is a particularly attractive option for neutral or basic wastes with low concentrations of plant-available heavy metals. For metalliferous wastes containing high residual metal concentrations and/or exhibit extremes in pH, direct establishment of normal plant material is not feasible and more refined techniques, such as the adaptive and/or the ameliorative approach are required. The adaptive approach involves direct seeding with metal-tolerant cultivars, the principle being to combat the toxicity of waste. The ameliorative approach relies on achieving optimum conditions for plant growth by either improving the physical and chemical characteristics of mine wastes using inorganic and/or organic amendments or by covering the wastes with inert materials (Tordoff et al. 2000). Direct seeding with metal-tolerant cultivars may provide an economic and practical solution, however, it leads to a restricted final land use. If a waste is to be used for amenity or agricultural purposes then the ameliorative approach may be more appropriate, especially if ameliorants are locally available. The tailings characteristics, particularly chemical parameters as well as site conditions determine which revegetation approach is most suitable. Thorough planning including detailed analytical studies, glasshouse pot tests and field trial programmes is thus essential for successful revegetation. Various approaches to revegetation depending on the waste characteristics are given in Table 10.

Table 10: Approaches to revegetation (Tordoff et al. 2000).

Waste characteristics	Reclamation technique	Problems encountered
Low toxicity. Total metal content: <0.1%. No major acidity or alkalinity problems	Amelioration and direct seeding with agricultural or amenity grasses and legumes. Apply lime if pH<6. Add organic matter if physical and chemical amelioration required. Otherwise apply nutrients as granular compound fertilisers. Seed using traditional agricultural or specialised techniques	Probable commitment to a medium/ long-term maintenance programme. Grazing management must be strictly monitored and excluded in some situations
Low toxicity and climatic limitations. Toxic metal content: <0.1%. No major acidity or alkalinity problems. Extremes of temperature, rainfall, etc.	Amelioration and direct seeding with native species. Seed or transplant ecologically adapted native species using amelioration treatments where appropriate	Irrigation often necessary at establishment. Expertise required on the characteristics of native flora
High toxicity. Toxic metal content: >0.1%. High salinity in some cases	(1) Amelioration and direct seeding with tolerant ecotypes. Sow metal- and/or salt-tolerant ecotypes. Apply lime, fertiliser and organic matter, as necessary, before seeding	Possible commitment to regular fertiliser applications. Relatively few species have evolved tolerant populations, and of those that have very few are available commercially. Grazing management not possible
	(2) Surface treatment and seeding with agricultural or amenity grasses and legumes. Amelioration with 10±50 cm of innocuous mineral waste and/or organic material. Apply lime and fertiliser as necessary	Regression will occur if depths of amendment are shallow or if upward movement of metals occurs. Availability and transport costs may be limiting
Extreme toxicity. Very high toxic metal content. Intense salinity or acidity	Isolation. Surface treatment with 30±100 cm of innocuous barrier material and surface binding with 10±30 cm of a suitable rooting medium. Apply lime and fertiliser as necessary	Susceptibility to drought according to the nature and depth of amendments. High cost and potential limitations of material availability

Direct revegetation was the closure option selected for the 310 ha tailings impoundment of Kidston Gold Mine in Queensland, Australia (Rykaart 2003). Overall the tailings have limited potential to generate acid, with the surface tailings (top 15 cm) having a lower acid generating capacity than the deeper tailings due to the processing of low grade ore in the latter stages of the impoundment life. The cover design was solely based on establishing vegetation and not for infiltration or oxygen control, and did not consider trafficability issues. Research towards the sustainability of the vegetation cover on the impoundment confirmed that a stable mix of native tree and shrub species can be applied by sowing seed directly into the tailings that would allow for natural succession to ultimately control the species longevity.

Direct revegetation of tailings was selected as the primary means of wind erosion control at the tailings impoundments of White Pine copper mine, Michigan, USA (Williams et al. 2002). The importation of sufficient clay material for covering the tailings facilities with a total area of 2,630 ha was estimated to cost over 72 million USD. The tailings have remained relatively barren for over 20 years. Factors that would adversely affect revegetation of tailings included lack of water and nutrient holding capacity, abrasion from saltating sand and silt, physical texture of tailings and chemical imbalances. In particular, copper was identified at potentially phytotoxic levels in the tailings. Based on the greenhouse and field trial test results, the revegetation technique implemented in full scale involved the treatment of tailings with local organic additives, such as paper mill sludge and wood chips and sowing with commercially available plants. Crimped straw mulch combined with revegetation was also identified as an effective means to control wind erosion, Figure 13 (a). An example of successful vegetation established at a tailings pond of Pb/Zn Tara mines in Ireland is shown in Figure 13 (b).

(a)

(b)

Figure 13: Rehabilitated tailings pond area at (a) White Pine mine, Michigan (Williams et al. 2002) and (b) Nava, Co. Meath, Tara mines, Ireland (Exploration and Mining Division Ireland 2004).

3.2.6 Wet versus dry covering

It is recognised that the stability of a tailings dam depends most fundamentally on whether or not ponded water is present on the surface of the tailings deposit. Given that, dry closure and permanent submergence differ markedly in their respective portfolio failure risks, i.e. the risk which accrues collectively over some inventory of individual risks. Based on the risk analysis presented by Vick (2001), for dry closure, the exposure period is limited essentially to the active life of the impoundment during mine operation, after which the probability of large-scale flow failure diminishes to effectively zero due to absence of surface water. Dry closure thus presents a low portfolio risk from the standpoint of physical stability. With good design and dam safety practices, it should be possible to achieve a safety level in the neighbourhood of 10^{-4}/dam-yr during active operation, similar to conventional dams, and no maintenance is required thereafter to assure physical stability. For permanent submergence, on the other hand, the exposure period is of unlimited duration because the water cover remains in perpetuity, while the inventory of such dams also continues to increase. Thus the portfolio risk for permanent submergence is very sensitive to the level of safety achievable in the long term and is also strongly influenced by the number of dams in the inventory.

Balanced against the risks to physical stability are those for chemical stability. To the extent that permanent submergence might be seen as more effective than dry closure in reducing ARD effects, this could offset its physical risks somewhat. The choice between these two closure strategies would therefore involve a trade-off between risks of a physical and chemical nature. A portfolio of impoundments employing dry closure might entail a greater risk of chronic, low-level ARD releases, but with little chance of much larger releases from catastrophic dam failure. Conversely, the geochemical security of permanent submergence may be associated with more long-term failures that increase exponentially with time. The nature of this trade-off largely depends on the site conditions. In general, permanent submergence will be more viable for sites conducive to long term stability, such as those with subdued topography, geologically mature landforms, and few seismogenic features. By contrast, permanent submergence can be viewed as altogether unsuited to areas of steep topography, active geomorphology or tectonics, or extremely high precipitation - all detrimental to long-term stability.

In the USA, the Environmental Protection Agency has not accepted permanent submergence as a long-term closure strategy and applies prescriptive standards requiring cap-and-cover closure for acid-generating tailings the same as for any other waste classed as hazardous. By contrast, permanent submergence has been endorsed by certain provinces of Canada where physiographic, climatic, and geologic factors are often favourable to long-term stability.

The costs and risks of the wet and dry rehabilitation options and associated strategies were compared in detail (paying special attention to dam safety) using a probabilistic approach at WISMUT. In densely populated areas (such as in Saxony with 247 inhabitants per km² and in Thuringia with 154 inhabitants per km²), where a 100% level of the probable equivalent costs was considered necessary, the dry landscape reclamation offered a better long term performance. However, the equivalent reclamation costs for the wet option remained up to the 65% probability level lower than for the dry option, thus presenting an efficient solution for the less populated remote areas.

A combination of a dry cover and a permanent water body will be applied for the tailings rehabilitation at Martha mine site, New Zealand (http://www.marthamine.co.nz/rehab_waste_disp.html). The dry cover will be placed adjacent to the embankments. Acid drainage control will be achieved by adding additional limestone to the tailings surface, and by achieving high levels of saturation within the tailings. The capping layer will consist of a running surface with a minimum thickness of 0.6 metres, covered by a layer of growing medium (Figure 14). This consists of a 0.5 m thick subsoil layer and a 0.1 m thick topsoil layer. This will be sown in pasture, and a littoral zone will be planted between the pasture and the pond edge.

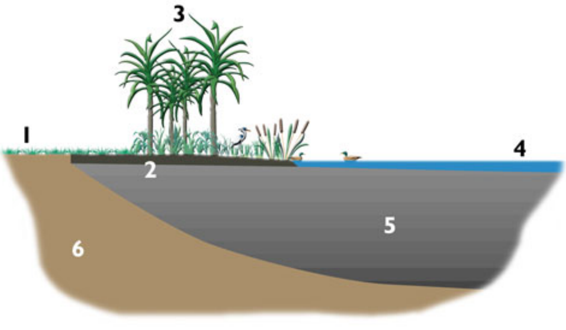


Figure 14: A conceptual cross-section of the littoral zone planting at the tailings storage facilities of Martha mine site, New Zealand.

1. Grassed Waste Rock Embankment crest. 2. Capping. 3. Planting of species such as cabbage trees, raupo and flaxes to provide nesting cover and food for birds. 4. Maximum pond level. 5. Consolidated tailings. 6. Waste Rock Embankment.

Some examples of closure technologies and associated cost recently implemented and/ or planned at TMFs in Europe are given in Table 11.

Table 11: Examples of closure technologies implemented and/ or planned at TMFs in Europe (data from BREF 2004).

Mineral	Site	Tailings closure technology	Cost
Bauxite	Ajka, Hungary	Dewatering and covering with 0.5 m of slag from power plant and a soil layer	
	Aughinish, Ireland	Closure plan involves the application of a vegetative cover on the mud stack	
Base metals	Aznalcóllar, Spain	Vegetated composite cover, consisting of: – 0.5 m protective soil layer and vegetation (top) – 0.5 m compacted clay, k: 10^{-10} m/sec – 0.1m blinding layer – 0.5 m waste rock, underlain by a geotextile layer – Additional measures involved construction of a stabilising berm, lowering the dam crest and resloping to 1:3 (V:H), construction of a cut-off wall with a network of pumping wells and drainage channels on top of the cover to manage surface runoff.	18.5 €/m^2
	Garpenberg, Sweden	Planning to – Cover the tailings surface with a vegetative cover – Cover the dams, which contain acid producing material with 1.1 m engineered soil cover, containing a 0.4 m compacted clay layer. Before covering, dams will be resloped to 1:2.5-1:3.0 (V:H)	
	Lisheen, Ireland	Closure plan involves the application of a water cover and wetland vegetation over the tailings, covering 64ha	Funds 14 million € (including aftercare)
	Pyhasalmi, Finland	Closure plan includes: – Covering of the tailings surface with 30 cm thick clay and silt layer overlain by 50 cm of moraine. – Maintenance of a water cover at TMF central part.	5.4 €/m^2 (includes closure and aftercare)
	Saxberget, Sweden	Vegetated composite cover, consisting of: – 0.3 m compacted clayey till, k: $5{\times}10^{-9}$ m/sec – 1.5 m unsorted till as a protection layer vegetated by grass and birch.	7 €/m^2
Precious metals	Bergama-Ovacik, Turkey	Closure plan involves covering with rock, gravel, clay and topsoil.	1.8 million USD
	Boliden, Sweden	Closure plan involves the application of a water cover	
	Rio Narcea	Closure plan involves dewatering, covering with soil and revegetation	

4. Post-closure monitoring

Post-closure monitoring is intended to evaluate the effectiveness of closure and rehabilitation measures. Data collected in a monitoring programme will determine whether the single high values are within a normal range for the particular site being monitored and will also provide the earliest possible warning if measures are unsuccessful. The monitoring must address physical stability, including the effects of static and dynamic conditions, and the chemical stability, which includes the prevention, migration and treatment control measures. Environmental impacts and the biological response also require monitoring on the site, in the downstream environment and in adjacent areas.

Closure monitoring should be based on the operational monitoring programme and focus on those aspects of the TMF that either relate to a potential ongoing pollution hazard or provide an indicator for how well the rehabilitation is progressing. The frequency of sampling and perhaps the number of sampling locations will generally decrease as the time after the closure increases. If significant changes in environmental conditions are detected at any station then additional monitoring should be introduced. If there is an adverse impact, alternative control or treatment techniques must be designed, tested and implemented. The monitoring programme then has to be revised to monitor the success or weakness of the added new measures. Current technology does not provide structures which can be expected to be effective for periods of hundreds or thousands of years. Therefore, monitoring of such structures as tailings dams and covers over potentially acid generating waste should be monitored for an extended time after closure.

Depending on the method of closure employed, post-closure monitoring may include visual inspections of site conditions, evaluations of embankment integrity, surface and ground water quality monitoring, assessments of the performance of stream diversions, seepage collection, and seepage treatment systems, and the success and progress of reclamation activities. Monitoring strategies for physical and chemical stability and vegetation establishment for disused tailings facilities are summarised in Table 12.

Table 12: Strategies for monitoring physical and chemical stability and vegetation establishment of TMFs (MIRO, 1999; Environment Australia, 2002).

Issues	Monitoring strategy
Physical stability	
• Access	*Visual* • Inspect ditches/berms/fences/signs
• Tailings and/ or cover stability	*Visual* • Look for gully erosion and seepage
• Dam stability	*Visual* • Look for signs of tension cracks at crest of slope, bulges at toe and new signs of failure and seepage • Look for seepage erosion or piping failure *Survey and/ or instrument if critical* • Rates of settlement and external deformation, seepage rates, internal deformation • Instruments-piezomenets for phreatic surfaces, inclinometer survey, settlement gauges
• Dam erosion	*Visual* • Look for gully erosion, alluvial fans, seepage *Sample* • Sample drainage for suspended solids
• Underdrains (water discharge)	• Survey discharge rates • Instruments-flow measurements
Chemical stability	
• ARD generation and/ or leaching of metals from tailings • Mill reagents in tailings	*Sampling and analysis* • Surface cover, tailings • Runoff • Seepage • Vadose zone drainage • Surface/groundwater downstream
Vegetation	
• Vegetation Establishment	• Transects, density, cover, diversity, photographic, regeneration

Rehabilitation environmental impacts and biological response should be monitored where conditions warrant. If impacts on the biological environment are not detected in the downstream environment during operation, then the level of biological monitoring after closure may be reduced to basic indicator species, to be defined for each specific site. If the site has a high risk of environmental impacts, it may be necessary to monitor biological parameters in more detail.

Vegetation monitoring is necessary to determine the success of rehabilitation and the recovery of the site. Natural ecological effects will therefore have to be monitored to determine whether the revegetation programme is successful and is progressing to a desirable, sustainable vegetative cover. Temporary effects which will influence the success of rehabilitation include depletion of nutrients, drought, fires, erosion, chemical uptake, species invasion and evolution (MIRO 1999).

5. Conclusions

Closure plans require a thorough re-assessment of the facility and its stability under closure conditions. All aspects of the facility and of the physical and chemical stability need to be reviewed. In particular, the actual performance of the facility in service, including deformation, seepage, foundation and sidewalls are checked against design projections, as well as against projected post-closure conditions. Design loads might be different after decommissioning and closure.

Although there is a number of different methods for construction and operation of tailings ponds, the problems associated with reclamation tend to be similar. Tailings have a very fine grain size and complete dewatering is very difficult under most climatic conditions. In some situations mining companies opted to store saturated tailings in a permanent pond on the surface, which means that the stability of the impoundment became imperative, even after the site has been reclaimed. The “dry” rehabilitation is, however, the preferable long term option in densely populated areas. In this case, from a geotechnical point of view the biggest challenge is the stabilisation of the very fine tailings (slimes). From an environmental perspective, the challenge is how to prevent the acid generation in tailings containing pyrite or other sulphides and control the contaminants release (such as As, Ra, U, Ni etc.).

There are a number of control technologies to consider for the closure of disused tailings facilities. The applicability of the options depends mainly on the conditions present at the site. Factors such as water balance, availability of possible cover material, groundwater level will influence the options applicable at a given site. Tailings ponds reclamation should be aimed toward a clearly defined future land use, whether active or passive for the area. Successful reclamation to a low maintenance land use, which is sustainable in the long term, requires an understanding of land forms, soil development and plant succession.

Structural monitoring and inspections need to be continued for tailings facilities until they are decommissioned, and thereafter as appropriate. Identification and delineation of any requirements for continuing inspection and/or the monitoring of remaining structures after closure is necessary. Action plans should be also prepared to deal with shortcomings in closure quality and/or difficulties in complying with closure specifications.

6. Case study – Reclamation of tailings ponds in Pécs, Hungary

6.1 Characteristics of tailings ponds

6.1.1 Mineralogy and Geology of the Mecsek Ore Deposit

The mineral components, associating and building up the ore-bearing sediments (the rock-forming minerals) are quartz (52.4%), feldspar (27.9%) in different forms, e.g. orthoclase, microcline, acidic varieties of plagioclase. Observed alteration are the kaolinisation and sericitisation of feldspars. In course of the lithogenesis, in action of diagenetic/epigenetic processes some part of feldspar dissolves. In connection with U mineralization, the displacement of feldspar by pyrite and U oxides (arcosic arenites) is observed. The occurrences of eruptive rhyolitic rocks, like lithic fragments in mineral association of the layers are one of the characteristic features of the Permian sediments in the Western Mecsek. Accessory minerals are zircon, apatite, tourmaline, muscovite, biotite, ilmenite and concerning the lithic fragments, rhyolites occur in 13.2%. Granitic originated (mostly microcline granite) fragments occur in 6.5%.

The percentage of matrix in average is 26.9%. The matrix of sandstone is constituted by hydromicas/illites (16.8%) and carbonate minerals (10.1%). The hydromica/illite matrix consists of Cr hydromuscovite (mekrohivite, Cr content 5-10%), hydrobiotite, common hydromuscovite (K 7-8%), green Cr illite, brown V illite, illite and phengitic illite minerals. Illite and phengitic illite are the most important components in the matrix of arcosic arenite layers. Carbonate minerals are calcite/dolomite, ankerite and siderite. The dolomite (ankeritic dolomite) prevails among the carbonate minerals.

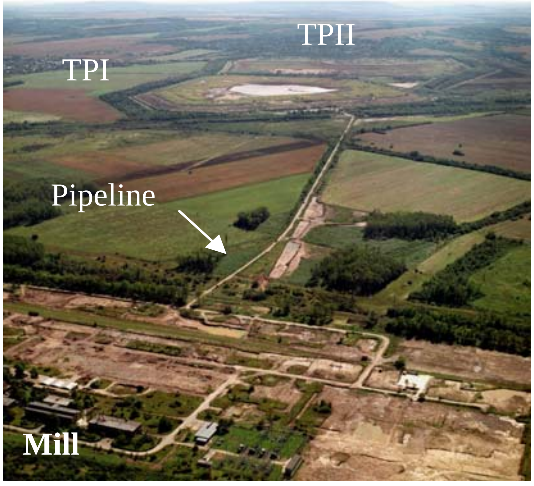
Fine crystalline (cryptocrystalline) quartz (in form of quartz-chalcedony) was formed from matrix feldspar. Some chlorite and apatite occur in matrix, too. The presence of Fe oxide, Fe hydroxide (hematite, hydrohematite) in the matrix shows close paragenetic connection with the U mineralization, in many cases.

In Western Mecsek, in accordance with redox conditions, there are two essential types of ore. The rust-coloured, so-called oxidised type ($2Fe_2O_3/FeO = 1.95$, $C_{organic} = 0.107\%$) and the grey coloured, so-called reduced type ($2Fe_2O_3/FeO = 1.1$, $C_{organic} = 0.340\%$).

The phases of the U ore minerals belong to the U oxide series and coffinite. The nasturan (pitchblende, pechblende) I, II, III, IV (pure mineral facies of U oxides) in bedded, cusps, globular precipitation forms, are the main mineral type in the grey (reduced) ore. Nasturan is partly post-coffinite pseudomorph. In contraction cracks of nasturan there are often galena, pyrite, and chalcopyrite filling. Coffinite occurs in all type of ores and sometimes constitutes an independent ore, with pyrite. The uranium-soot (nasturan + U hydroxide + coffinite + $C_{organic}$ + illites), as fine grained mineral aggregate, is typical of the oxidised ore type.

In Western Mecsek some of the secondary uranium minerals can also be found (uranyl carbonate, -sulphate, -phosphate). They occur under hypergenic conditions. The accompanying minerals in ore are mainly sulphide ore minerals associated with uranium ore mineralization such as pyrite, marcasite, galena, chalcopyrite, sphalerite, chalcosine, grey copper ore, and arsenopyrite.

Mined ore was radiometrically upgraded, then crashed, milled and leached with sulphuric acid. Uranium was removed by an anion exchange process. Yellow cake was precipitated with lime milk, and the obtained calcium diuranate was the commercial end product. Wastes from processing were treated with limestone and lime milk to pH~7. Two tailings ponds, tailings pond N1 (TPI) and tailings pond N2 (TPII) were built 2-4 km away from the mill for storing the neutralised tailings. Location of the two tailings ponds and the former mill is shown in Figure 15. The total area of tailings ponds (TP) is 154 ha. Tailings were transported to tailings ponds (TP) by pipeline. Approximately 14.2 and 4.6 Mt of tailings were disposed off in TPI and TPII respectively. TPI is rather a ring dyke, while TPII belongs to the valley-type. TPI had been operating since 1997, TPII only since 1991 (therefore it was almost dry in 1998 when remediation works started).



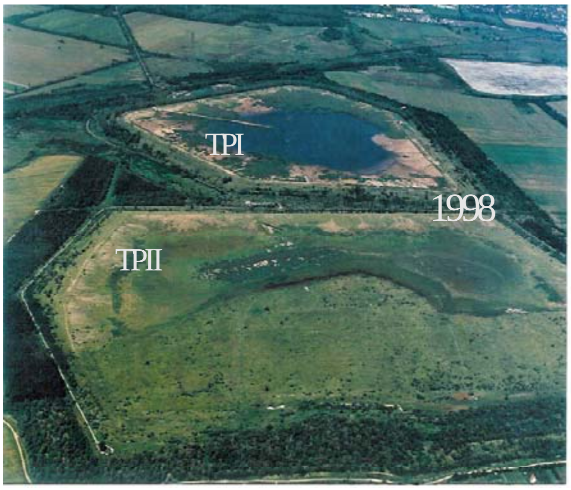


Figure 15: Location of the mill and the two tailings ponds (mill area is fully remediated).

As seen in Figure 15, the tailings in TPI were very weak and part of them was even under water in 1998. Thus for the design and application of remediation actions, careful investigation of the tailings was required. The studies included examination of the mineralogical composition of the tailings, determination of the physical characteristics and chemical composition, geotechnical investigation, etc. The results of the investigation studies performed and the remediation measures applied subsequently are described in the following paragraphs.

6.1.2 Mineralogical composition of tailings

Deposition of tailings was performed after the separation of the coarse sand fraction for dam construction by hydrocyclones. As a result, tailings ponds practically consist of three zones:

- Fine slime zone
- Intermediate zone
- Sandy zone (dam)

Due to the segregation of materials the three zones present different mineralogical composition. Dam material consists mainly of quartz, while the slimes contain silt, gypsum (formed during the leaching) etc. Details on the mineralogical composition are given in Table 13.

It is seen that the fine tailings contain an extremely high volume of gypsum (which seems to be concentrated in this fraction of tailings). The clay minerals are present in the finest tailings. The clayey part of tailings was separately investigated for montmorillonite content to receive information regarding the possible thixotropy (liquefaction behaviour) of tailings. It was determined that the content of montmorillonite is low and occurs only in form of mixed-layer illite-montmorillonite. Therefore, the average content of montmorillonite in fine tailings is as low as 6-8 %. Such low montmorillonite content can not lead to the liquefaction of fine tailings.

Table 13: Mineralogical composition of fine tailings.

Mineral	Formula	Amount of minerals (%)		
		I.Z.K	**I.Z.D**	**II.Z.D**
Bassanite	$CaSO_4 \cdot 0.5H_2O$	16	17	37
Gypsum	$CaSO_4 \cdot 2H_2O$	40	31	4
Feldspar	NaAlSi3O8	13	8	7
Quartz	SiO2	19	20	18
Muscovite	$KAl_2(Si_3Al)O_{10}(OH)_2$	3	3	3
Clay minerals (illite, montmorillonite)	$Na_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2$	8	18	28

I.Z. K (TPI, fine tailings zone, east part)
I.Z. D (TPI, fine tailings zone, south part)
II.Z. D (TPII, the finest tailings zone, south part)

6.1.3 Grain size distribution of fine tailings

A percentage of 40% of tailings had grain size >0.1 mm and 60% <0.1 mm, however, significant segregation of the tailings took place during their deposition by hydrocyclones. Fine tailings were analysed with Marveln laser analyser. It was found that 90% of fine tailings, mainly found in the slime core (central part) of tailings ponds, had grain size finer than 0.05 mm.

6.1.4 Chemical characteristics of tailings

The chemical composition of three samples collected from different part of the tailings ponds (one from the dam, one from the intermediate zone and one from the fine tailings zone) is given in Table 14. It is seen that the heavy metal content of tailings is low. Practically only manganese (which was used as oxidising agent) and vanadium content present elevated values. The tailings do not exhibit net acid generation potential, because their pyrite content is low (in the processed ore <0.2%).

6.1.5 Geotechnical characteristics of tailings

As it was referred in previous paragraphs, due to the tailings deposition method the tailings ponds practically consist of three zones (fine slime, intermediate and sandy zone). Figure 16 presents the in situ measurements of the shear strength on TPI, the tailings sampling (A) using boot constructed from empty (but closed) barrels, and the shear strength values for fine tailings and transition zones (B) vs. depth of tailings. Shear strength was measured up to 9 m below water level. As seen in Figure 16, the fine tailings have very low shear strength under water, i.e. <5 kN/m^2, which became higher at greater depth. In the transition zone values are a little higher (5-15kN/m^2), whereas the values of the shear strength in the sandy zone were high (>40 kN/m^2). In any case, an area of approximately 13 ha in the fine slime zone needed stabilisation prior to start the covering workings.

Table 14: Elemental analysis of tailings.

Number	Element	ZT I 14/1 6-17 (R4176)		I. Z. D		TP II Dam	
		Concentration	StdErr	Concentration	StdErr	Concentration	StdErr
		%		%		%	
Sum Be..F	Be-F		0,073	0	0,08	0	0,086
11	Na	0,48	0,02	0,51	0,03	0,98	0,04
12	Mg	1,14	0,04	2,46	0,06	0,51	0,02
13	Al	6,09	0,08	4,5	0,07	6,21	0,08
14	Si	19,3	0,1	13,8	0,1	29,3	0,1
15	P	0,058	0,004	0,052	0,004	0,03	0,002
16	S	0	0,56	0	0,71	0	0,26
16	So	5,71	0,07	7,21	0,08	2,62	0,05
17	Cl	0,19	0,01	0,47	0,03	0,003	0,002
18	Ar	0	0,001	0	0,001	0	0,002
19	K	3,68	0,08	2,71	0,07	4,73	0,09
20	Ca	6,6	0,1	9,9	0,1	3,89	0,08
21	Sc	0	0,0008	0	0,0008	0	0,001
22	Ti	0,26	0,02	0,2	0,01	0,27	0,02
23	V	0,056	0,004	0,067	0,005	0,56	0,004
24	Cr	0,011	0,001	0,0095	0,0008	0,015	0,001
25	Mn	0,94	0,04	1,5	0,05	0,28	0,02
26	Fe	2,89	0,07	2,79	0,07	1,48	0,05
27	Co	0,0055	0,0007	0,0029	0,0007	0,001	0,0007
28	Ni	0	0,0009	0	0,0009	0	0,0009
29	Cu	0,0066	0,0007	0,002	0,0006	0,0046	0,0008
30	Zn	0,0109	0,001	0,03	0,003	0,0105	0,0009
31	Ga	0,001	0,0004	0,0011	0,0004	0,0007	0,0004
32	Ge	0,0006	0,0005	0	0,0003	0,0003	0,0003
33	As	0,012	0,001	0,009	0,001	0,01	0,001
34	Se	0,0031	0	0,003	0,0004	0,0019	0,0004
35	Br	0	4	0	0,0003	0	0,0003
37	Rb	0,014	0,0003	0,0101	0,0009	0,019	0,002
38	Sr	0,029	0,001	0,031	0,003	0,024	0,0004
39	Y	0,0039	0,002	0,003	0,0004	0,0017	0,001
40	Zr	0,015	0,0005	0,0105	0,0009	0,021	0,001
41	Nb	0,0003	0,001	0	0,0003	0,0003	0,001
42	Mo	0	0,0003	0	0,001	0	0,0009
44	Ru	0	0,001	0	0,001	0	0,0008
45	Rh	0	0,001	0	0,001	0,001	0,0009
46	Pd	0	0,001	0	0,001	0	0,001
47	Ag	0	0,001	0	0,0008	0	0,001
48	Cd	0,0008	0,001	0	0,0008	0,0014	0,002
49	In	0	0,0008	0	0,0007	0	0,003
50	Sn	0	0,0008	0	0,0009	0,0008	0,006
51	Sb	0	0,0009	0	0,0009	0	0,029
52	Te	0	0,0009	0	0,001	0	0,001
53	I	0	0,001	0	0,001	0	0,001
55	Cs	0	0,001	0	0,002	0	0,001
56	Ba	0,042	0,001	0,041	0,003	0,069	0,001
Sum La..Lu	La-Lu	0,009	0,002	0,014	0,027	0,012	0,001
72	Hf	0,002	0,004	0,001	0,001	0	0,001
73	Ta	0	0,026	0	0,001	0,002	0,001
74	W	0	0,001	0	0,001	0	0,001
75	Re	0,002	0,001	0	0,001	0,003	0,001
76	Os	0,001	0,001	0	0,001	0	0,001
77	Ir	0,001	0,001	0	0,001	0	0,001
78	Pt	0	0,0008	0	0,0009	0	0,001
79	Au	0,0004	0,0008	0	0,0009	0	0,001
80	Hg	0,0009	0,0008	0	0,0009	0,0008	0,001
81	Tl	0	0,001	0	0,001	0	0,001
82	Pb	0,022	0,002	0,032	0,003	0,0018	0,002
83	Bi	0	0,0007	0	0,0009	0,001	0,001
90	Th	0,001	0,001	0	0,001	0	0,002
92	U	0,008	0,001	0,024	0,002	0,014	0,001

I. Z. D.	**TP I, south part**
TP I 14/1 6-17 m	**TP I, intermediate zone**
TP II Dam	**TP II, from the dam**

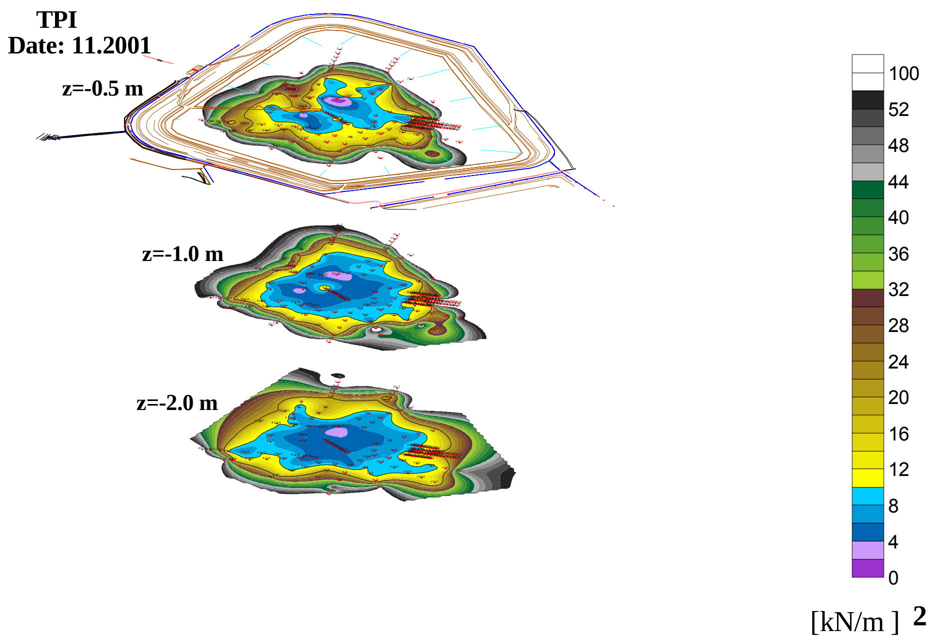


Figure 16: In situ shear strength measurements on TPI.

6.1.6 Radiological characteristics

In Hungary relatively low-grade ore was processed, therefore radio-elements are also present in the tailings in low concentration. Nevertheless, the major part of the radioactive nuclides contained in the ore are also present in the tailings, because the mill process recovered only uranium (app. 90% of it), and tailings practically contain all other decay products of uranium. Therefore, the total activity for the ore with 0.1% of original uranium (Hungarian ore grade) is on the level of 170 Bq/g. Due to the radium content (12 Bq/g) tailings show radon exhalation value, which depends on the physical characteristics of tailings (water content, porosity, grain-size). Actually, the radon exhalation rate of the dam is in between 3-8 Bq/m^2/s, two orders of magnitude higher than the background level.

6.1.7 Composition of tailings water

Tailings water was highly contaminated with non-radioactive components originating from the leaching process. The composition of process water discharged at the tailings ponds together with solid tailings has changed depending on the used technology. Taking into account the volume of process water and τηε quantity of reagents used, etc. the average TDS in tailings water was estimated to app. 20-22 g/l. The high TDS in process water was due to the relatively low pH (~7-8) on the stage of the barren pulp neutralisation. At that pH, the main part of magnesium sulphate remained in the neutralised solution.

The tailings were deposited in ponds constructed without or with very poor sealing. Therefore, process water from the tailings ponds could partly have seeped into the soil beneath the ponds. According to the estimations approximately 20 Mm^3 of process water (from the total of 32 Mm^3) seeped into the soil beneath the ponds over the operation period of the mill. Based on these calculations the quantity of chemical compounds seeped from tailings into the surroundings was estimated to 400 kt or even more. Groundwater contamination was detected as early as in 1977, but systematic site investigations and monitoring started only in 1989.

6.2 Reclamation workings

Remediation of tailings ponds dealt with the:

- Water management
- Stabilization of fine tailings
- Recontouring the dam and relocation some part of tailings
- Covering
- Revegetation
- Groundwater restoration

6.2.1 Reconstruction of the toe drain

Toe drain system of both tailings ponds was examined in detail by camera and new discharge pipes were installed. The collection ring pipe line was placed in earth and the former ditch for seepage was reconstructed for the collection of non-contaminated run-off water. In this way the two types of water will be collected and if required treated separately. Characteristics photos of the toe drain reconstruction workings are presented in Figure 17.

Figure 17: Reconstruction of the toe drain.

6.2.2 Covering

The first step for the long-term stabilization of tailings ponds was the stabilization of the very weak fine tailings covering an area of 13 ha in TPI. Due to the fact that TPII has been out of operation for some years, all the three zones were stable enough and therefore, surface stabilisation was not required.

For the stabilisation of fine tailings in TPI, dewatering by earth loading and removing of compression water with drainage was recommended as the most reliable method (Wismut and C&E 1999). To prepare the fine slime zone for stabilisation, at first the free water was discharged from the tailings pond (Figure 18). As a result, the surface of fine slimes became stable enough in some months.

Following dewatering, geotextile and geogrid were used for further stabilisation, as shown in Figure 19.

Figure 18: Fine tailings zone after free water discharge and some months of desiccation

Figure 19: Placement of geogrid, vertical drains and loading the enforced surface.

A 0.5 m sand layer from dam recontouring (app. 0.8 Mm^3) was placed on the geogrid, overlain by a layer of material loaded from different parts of the dam. The former central absorbing well collected the deliberated (free) water from consolidation process (the well earlier was used for water recycle). To enhance the stabilisation vertical drain was also used.

Selection of covering option

The aims of tailings covering included:

- To prevent the dispersion of hazard material In the case of uranium mill tailings to decrease radon exhalation and gamma-dose rate;
- To prevent water contamination (or to attenuate at least) from seepage by decreasing the seepage rate through the tailings;
- To decrease the unauthorised removal of hazard material;
- Long-term stabilization of tailings pile.

To select the appropriate cover configuration, an extensive modelling work was undertaken with the participation of Wismut GmbH. Estimation of the seepage rate was carried out using the HELP model. Depending on the criteria different designs have been used in practice. In Hungarian case “The Environmental License for Remediation” regarding the covering claims among others:

- To reduce the radon flux (max. 0.74 Bq/m^2s
- Decrease of gamma-dose rates (max. 300 nGy/h)
- Minimisation of the seepage rate
- Design life 200 years

Site-specific design criteria were:

- Minimisation of radon flux because the tailings ponds are located close to villages with more than ten thousand inhabitants;
- Minimization of seepage rate through the tailings ponds because of the necessity of the protection of drinking water aquifer in the immediate vicinity of tailings piles.

Therefore, the design must consist of a sealing layer with low permeability, a water storage layer for further inhibition of water infiltration and vegetation to increase the evapotranspiration rate and erosion protection. Also a drainage between the water storage layer and sealing layer is desirable to protect the sealing layer from root intrusion, animal intrusion etc.

For calculation with HELP model the following material data were used:

- Porosity,
- Field capacity,
- Wilting point,
- Hydraulic conductivity for the particular materials.

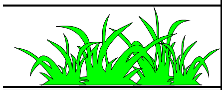
Special institutions determined the above soil characteristics. Sensitive analysis was carried out among others for:

- Water storage layer (effective depth of root penetration 50, 60, 80, 100 cm, k-value: $1x10^{-6}$, $8x10^{-9}$ m/s);
- Sealing layer (k-value: $1x10^{-8}$- $5x10^{-10}$ m/s, 30, 40, 50 cm);
- Slope of the surface (5-20%);
- Length of run-off on the surface (20, 30, 250 m).

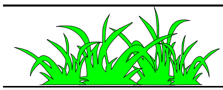
Following the evaluation of different options, two design types were selected (Figure 20):

Option 1/1 for TPII, and
Option 2/1 for TPI.

Cover design for TPII: Loess with sand drainage and clay as sealing layer

	Layer Type	Material
	vegetation	grass and bushes
0,6 m	storage layer	loess
0,3 m	drainage layer	sand
0,3 m	protection layer	compacted loess
0,3 m	sealing layer	clay
		tailings

Cover design for TPI: Loess cover with clay as sealing layer

	Layer type	Material
	Vegetation	Grass and bushes
0,4 (0,45) m	Storage layer	Loess (degree of compaction ≤90%)
0,4 (0,45) m	Storage layer	Loess (degree of compaction 90 to 93%)
0,4m	Protection layer	Compacted loess 2 (compaction app. 95%)
0,4 (0,3)m	Sealing layer	Compacted clay (compaction 95 to 97%)
	Tailings	

(Data in bracket for dams)

Figure 20: Covering options for TPI and TPII (Hungary).

The water balance for the two options is presented in Table 15.

A sand drainage layer was not included in the cover design of TPI because the settlement of this pond is still in progress and it may result in the formation of a "water sack" in some spots of the fine tailings area because of unequal consolidation rate on the area after covering (deformation of layers). The formed "sacks" can lead to a more intensive seepage rate. It is also possible that the drainage will lost in some extent of its water conductivity because of the layers deformation.

According to the modelling it can be expected that the seepage rate from the tailings pile will be on the level of 30 mm/a, which complies with the Environmental Licence.

Table 15: Water balance for the two cover options.

Option	Layer sequence	Material	k-value	Thikness	Eff. evap. zone	Run-off	Ev.transp.	Drainage	Seepage
			m/s	m	m	mm/a	mm/a	mm/a	mm/a
1/1	Water storage layer	Loess		0.6	0.6	21	505	109	**21**
	Drainage	Sand	5.00E-05	0.3					
	Protecting layer	Comp. loess	5.00E-07	0.3					
	Sealing layer	Clay	1.00E-09	0.3					
2/1	Water storage layer 1	Loess	8.00E-08	0.45	~0.9	42	565	0	**30**
	Water dtorage layer 2	Slightly comp. loess	2 E-8	0.45					
	Protecting layer	Compacted loess	2.00E-08	0.4					
	Sealing layer	Clay	1.00E-09	0.3					

Annual precipitate: 649 mm (1990-1998 átlaga)
Option 1/1 for TPII
Option 2/1 for TPI

For the calculation of the expected radon exhalation rate there are some internationally recommended equations (IAEA 1992):

$$F_c=F_t \exp (- (\tilde{\lambda}/D_c)^{1/2}*x_c) \qquad (1)$$

(F_c radon flux from covered tailings pile, F_t radon flux from uncovered tailings, λ decay constant of radon, D_c diffusion coefficient, X_c thickness of the covering layer)

Basic data in all equations is the diffusion coefficient of the radon, which strongly depends on the porosity and the saturation of the covering soil, based on equation (2):

$$D = 0.07\exp[-4(m - mn^2 + m^5)] \qquad (2)$$

(m moisture saturation, n porosity)

Using the recommended evaluation procedure it can be determined that the radon flux from tailings covered with soil (thickness 1.5 m) will be much below the limit (0.74 Bq/m^2/s). This is demonstrated in Figure 21, where radon exhalation rate is presented for different cover and tailings saturation for cover thickness of 1.5 m (Wismut 1998). It can be seen that the radon flux remains below the limit even if the moisture content is far from saturated state.

The attenuation of radon concentration for the layer sequence in the cover proposed for TPII is presented in Figure 22. It is deduced that the radon concentration drops very sharply in the radon barrier constructed from clay and compacted loess, whereas the overlying layers have only a little effect on it.

Characteristic photos of the construction of the covers are shown in Figure 23.

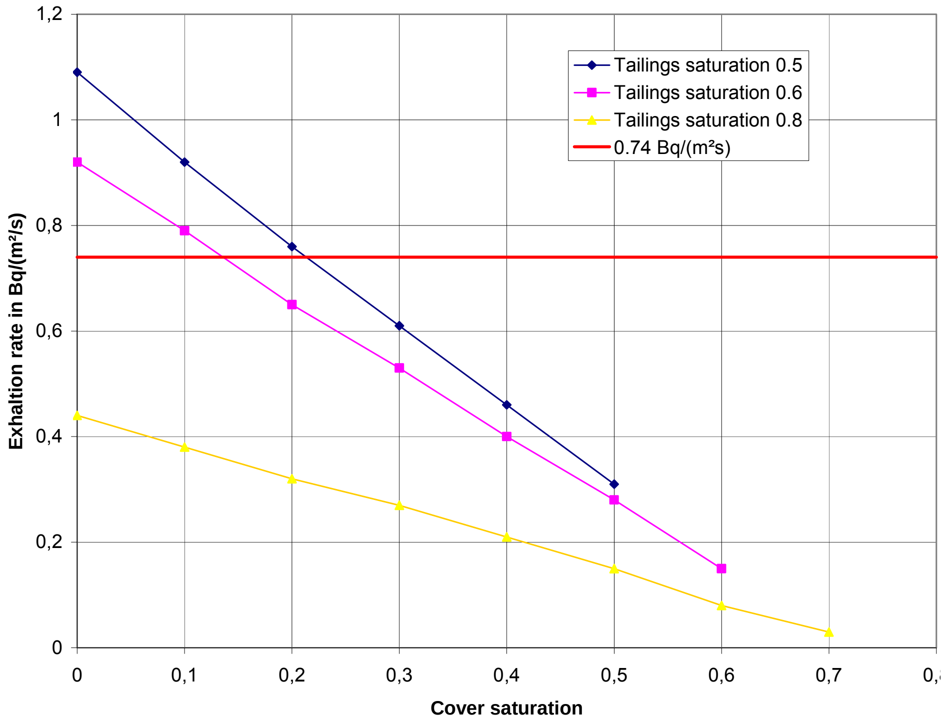


Figure 21: Radon exhalation as a function of soil and tailings saturation (thickness 1.5 m).

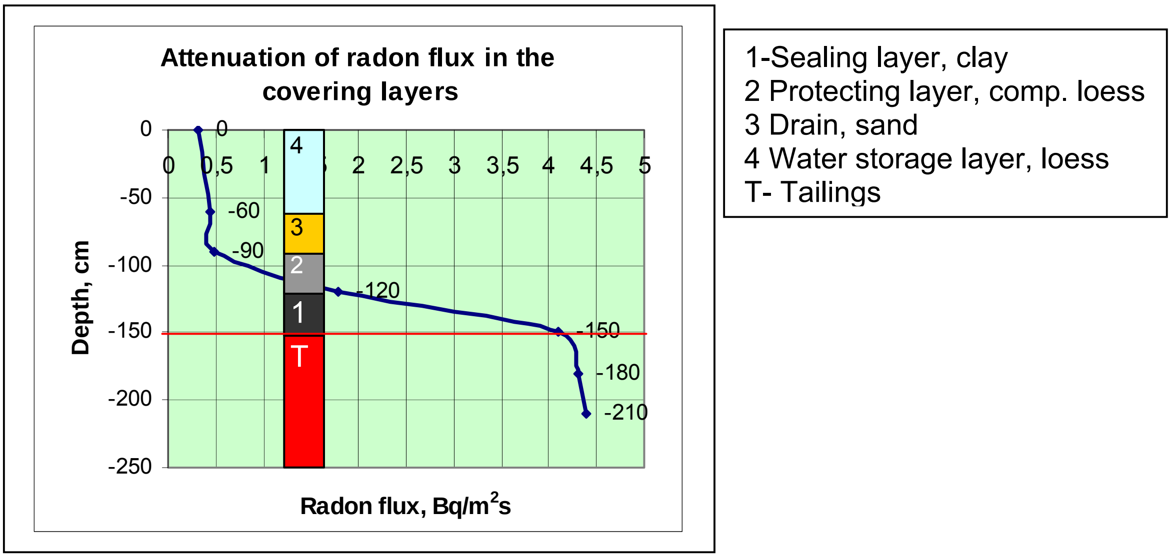


Figure 22: Attenuation of radon concentration in the cover.




Figure 23: Placement of covering layers.

6.2.3 Revegetation

Revegetation plays an extremely important role in the performance of a cover regarding its effectiveness in reducing the seepage rate and ensuring erosion stability. Erosion protection is a huge problem when a pile is covered. In Figure 24 some erosion galleys formed soon after covering of the tailings ponds during a summer heavy rainfall can be seen.

Figure 24: Water erosion observed on TPI.

Revegetated areas on tailings ponds are shown in Figure 25. The revegetation included seeding of grass and plantation of bushes and trees (21 species) as follows:

Seeds of grass:	200 kg mixed grass seeds / ha	
Bushes or seedling:	8 000 pieces/ha (1-2 years old). Distance between the rows: 2,5 m.	
Chemical fertiliser:	N	120 kg/ha
	P_2O_5	100 kg/ha
	K_2O	170 kg/ha

Figure 25: Establishment of vegetation on TPI.

6.3 Monitoring of the performance of reclamation measures

The implementation and performance of reclamation measures have been monitored in accordance with the adapted quality insurance. This activity can be divided into two main parts:

- Monitoring of the cover during its construction;
- Monitoring of the covered tailings piles.

6.3.1 Monitoring of the cover during its construction

Prior to start covering workings, for the selection of cover materials, the characteristics of candidate materials including chemical composition, mineralogical composition, and soil mechanic characteristics were determined. According to the instructions, these parameters have to be determined every 50 thousand m^3. Very important data are the Proctor-curves on the basis of which the optimal water content of the layer is determined. Parallel with placing the sealing layer, in situ *k-v*alue determination was carried out using simple infiltrometer (Figure 26). Measurements were performed every 500 m^2.

Figure 26: In situ determination of *k*-value of the constructed sealing layer.

Compaction and the thickness of the sealing layer was measured by PANDA penetrometer (Figure 27), which determines the cone resistance (MPa) depending on the type of material, its density and thickness. The “handy CPT” proved to be a valuable device for the determination of the homogeneity of the earth layer. Therefore it is used for measuring the thickness of cover design and its compaction too.

For controlling of the moisture in sealing layer Mobile Moisture Meter was used (Figure 28), which is recommended for measurement of volumetric moisture in porous material. Operating principle is based on measurement of the dielectric constant of materials. Measuring range is 0-90%. It proved to be a reliable instrument for rapid in situ determination of the moisture content of the soil.

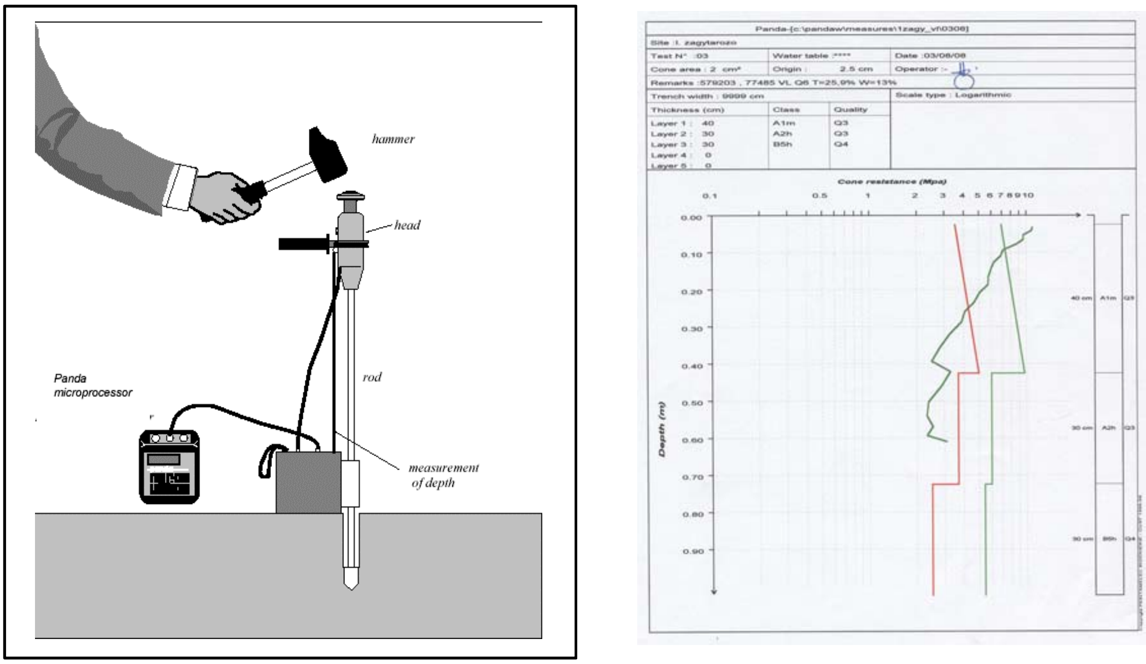


Figure 27: PANDA penetrometer for measurement of layer thickness and compaction.

Figure 28: Rapid field moisture determination (TRIME® FM).

6.3.2 Post remediation monitoring

Remediated tailings ponds have to be monitored for long time. Frequency of the monitoring will be decreased by time but during the initial period an intensive monitoring program should be undertaken. Sampling and onsite monitoring is carried out in accordance with the annual monitoring program approved by the authorities.

Radiological monitoring

This work involves the measurement of radioactivity in the vicinity of inhabited areas, regular measurement of aerosols, and radon exhalation on the covered tailings ponds. A monitoring station is installed in the nearby villages for continuous monitoring of the ambient gamma dose rate, radon and its progenies concentration, long-lived alpha-contamination of aerosols and a cumulative additional dose is calculated for every month. Data are hand over to the municipalities.

Consolidation process

To monitor the consolidation process of the tailings, settlement is measured monthly. 166 settlement-gauges have been installed. The data collected are subsequently processed and evaluated, as shown in Figure 29. Based on the results, it is seen that the largest settlement has taken place in the central part of the TPI on fine tailings area, as expected.

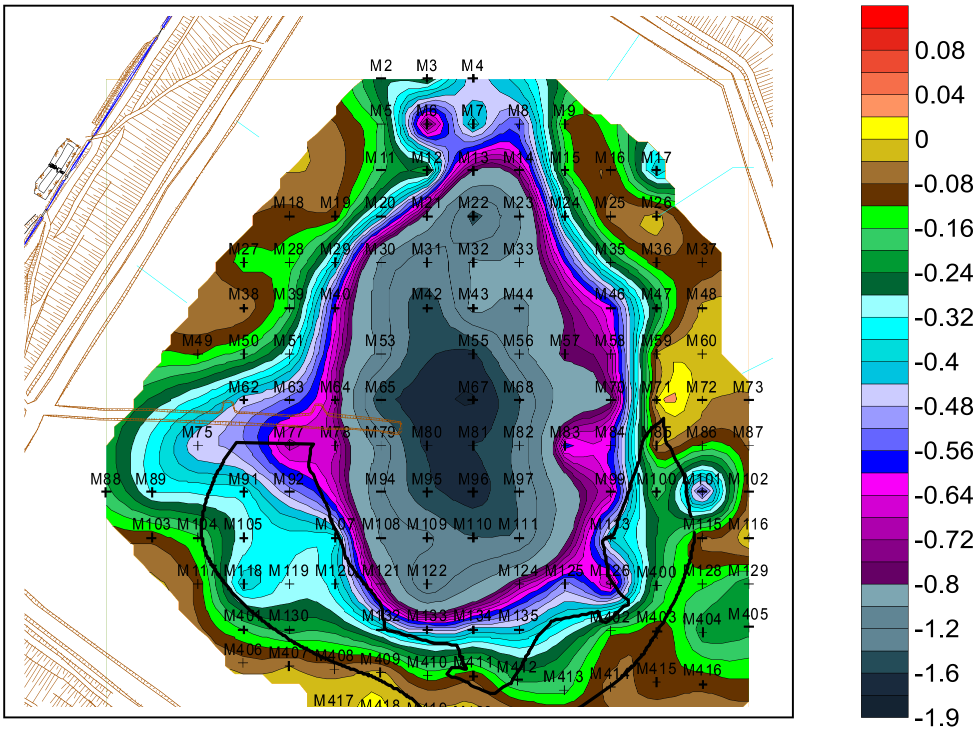


Figure 29: Monitoring of the consolidation process (settlement) on tailings piles.

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