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CLOSURE OF TAILINGS FACILITIES: CURRENT PRACTICE REVIEW & GUIDELINES FOR SUCCESS

Mark Robins

A research project submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering (Civil).

Johannesburg, 2004

I. CANDIDATE'S DECLARATION

I declare that this research project is my own, unaided work and is submitted for the degree of Master of Science in Engineering (Civil) in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed,

……..
Mark Robins

This …….. day of ……..…., 2004.

II. ABSTRACT

This research project has been prepared to satisfy the requirements of the University of the Witwatersrand, Faculty of Engineering and the Built Environment for the degree of Master of Science (Civil) in Geotechnical Engineering and Materials (50/50).

Contained within the project is a review of international past and current tailings facility closure techniques. Guidelines and minimum requirements for successful closure have been developed and are presented.

III. ACKNOWLEDGEMENTS

Gratitude and appreciation is expressed to:

- AngloGold Ashanti Ltd and its personnel worldwide for the use of much of the material contained within this report and for allowing free access to company operations and information.
- Mr. WR Lethlean, Head of Metallurgy, Corporate Technology Group, AngloGold Ashanti Ltd, for his enthusiastic support and mentoring.
- Professor A Fourie of the University of the Witwatersrand for his mentoring, assistance and guidance.
- Mr. BW Guenther, Head of the Corporate Technology Group, AngloGold Ashanti Ltd for his approval to submit this work.
- Mr. A Mackenzie, Environmental Manager, AngloGold Ashanti Ltd for information and photographs.
- Messrs. JA Wates and T Lloyd of Golder Associates (Africa) for information.
- Mr. D Cameron of Anglo American plc (Technical Division) for information.
- Mr. PB Swart, Remediation Project Leader, Environmental Management Department of AngloGold Ashanti (South Africa Region) Ltd for his generous assistance.
- Mr. NH Theunissen, Manager Environmental Services, South Africa Region Metallurgy, AngloGold Ashanti Ltd for information and photographs.
- Mr. H Geldenhuys of AngloGold Ashanti for his time and assistance.

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V. LIST OF SYMBOLS

Système International d'Unités (SI) units and symbols have been used throughout.

VI. NOMENCLATURE

Definitions

The following definitions apply within the context of this report:

WORD/TERM:	DEFINITION:
Acceptable environmental impact:	An *acceptable* environmental impact is one in which the potentially adverse influences have been minimised as far as possible using *BACET* and which are within limits stipulated by the regulatory authorities and other stakeholders.
Analogue site	A site selected to be fully representative of the site disturbed by mining prior to the disturbance.
Appropriate containment:	*Appropriate containment* is the mitigation of seepage to result in *acceptable environmental* ground or surface water *impacts.*
As-built drawings:	Engineering drawings that record the facility as constructed immediately prior to commissioning.
As-built records:	Engineering reports that detail the construction activities and document test results and problems or changes encountered.
Best Practice:	*Best Practice* is referred herein to establish a benchmark against which the performance of a tailings facility can be measured. In the absence of internationally accepted standards in the tailings industry *Best Practice* is commonly accepted as being the standards typical of current good practice in North America for similar structures, although examples of *Best Practice* can also be found elsewhere.
Closure:	*Closure* will have been achieved when all appropriate steps have been taken to ensure that the tailings facility is in a state where all necessary legislative and regulatory approvals have been obtained to discontinue active management of the facility.
Commissioning:	The functions that precede the routine operation of the tailings facility, i.e. design, construction and certification.
Commitments to	Obligations made to persons or organisations that have an interest in the tailings

stakeholders:	facility.
Continual improvement:	The process of enhancing the tailings facility management system to achieve ongoing improvement in performance in stability, safety and/or environmental performance.
Decommissioning:	The activities or processes that begin after cessation of prospecting activities or mineral production and ends with *closure*.
Design:	*Design* is the: • Application of rational engineering and scientific principles to the selection of exploration of sites for tailings facilities. • Establishment and measurement of characteristics and properties of the residue and the *in situ* properties of the site, including hydrological conditions. • Establishment by means of calculation, suitably qualified judgement and experience of a layout arrangement and dimension that will result in a safe and economical deposit.
Environmentally responsible:	*Environmental responsible* tailings management is achieved after identification and mitigation of all potential environmental impacts so that they *become acceptable environmental impacts*.
Environmental protection:	Measures taken to safeguard the environment and to minimise the impact of tailings-related activities.
Freeboard:	The vertical distance between the water/fluid pool surface and the lowest point on the dam wall.
Growth medium	Uppermost layer provided to support vegetative cover.
Liner:	A tailings facility *liner* is a low-permeability barrier provided to all, or part of a tailings facility to reduce seepage and provide *appropriate containment*. *Liners* may be partial or full liners, consisting of compacted *in situ* material, imported clays, or synthetic membrane or combinations thereof. Drainage systems are usually provided to protect the liner.
Mine residue:	Waste rock, slimes or tailings derived from the mining operation or processing of gold-bearing ores.
Precautionary Principle:	This principle states that: 'where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used a reason for postponing measures to prevent environmental degradation'. In other words, mining operations should take active steps to deal with potentially serious pollution immediately and not defer protective measures until the problem has manifested itself fully.

Reference site	A site selected to be representative of the site disturbed by mining after rehabilitation.
Rehabilitation/ reclamation	The process used to repair the impacts of mining on the environment. Referred to as reclamation in North America.
Safe:	A *safe* state is achieved when the facility does not add significantly to the total risk to which employees, the public and the environment are exposed.
Significant risk:	A *significant risk* is one that adds appreciably to the total risk to which employees, the public and the environment are exposed.
Stable:	Tailings deposits are considered to be *stable* when they pose low potential for rapid release of tailings or pollutants to the environment.
Stakeholder	Person, or persons, organisations or communities that have an interest or stake in the tailings facility or its impacts.
Tailings:	Mine residues from the metallurgical processing of gold-bearing ores finer than 2mm are regarded as *tailings*.
Tailings facility:	All components and activities associated with tailings delivery, deposition and storage, including all civil, mechanical and electrical infrastructures. It also includes all components and activities associated with the collection and return of tailings decant water, and the collection and disposal of seepage. *Tailings facilities* are also referred to as tailings containment facilities, tailings dams and slimes dams.
Topsoil	Material removed from the tailings facility site prior to commissioning or elsewhere for use in rehabilitation usually to form the growth medium layer.

Abbreviations

The following abbreviations apply within the context of this report:

ABBREVIATION:	DEFINITION:
ACG	Australian Centre for Geomechanics
AGP	Acid generating potential
ARD	Acid rock drainage, acid mine drainage or acid drainage
As	Arsenic
BACET	Best available cost effective technology, which implies that the technology being considered is proven by practical application appropriate to the particular problem and generally accepted by the industry at the time
BATNEEC	Best available technology not exceeding excessive cost

CDA	Canadian Dam Association
CAPEX	Capital expenditure
COMSA	Chamber of Mines of South Africa
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Central thickened discharge
EFA	Ecosystem function analysis
EIA	Environmental impact assessment
EPA	Environmental Protection Agency
EMP	Environmental management programme
HDPE	High density polyethylene
ICMM	International Council Mining and Metals
IIED	International Institute for Environment and Development
IFC	International Finance Corporation – A division of the World Bank
LFA	Landscape function analysis
MAE	Mean annual evaporation
MAP	Mean annual precipitation
MCE	Maximum credible earthquake
MMSD	Mining, Minerals and Sustainable Development
NPV	Net present value
NGO	Non-governmental organisation
OPEX	Operating expenditure
PMF	Probable maximum flood
QA	Quality assurance
QC	Quality control
SABS	South African Bureau of Standards
SEA	Strategic environmental assessment
SI	*Système International d'Unités* units
SPG	Specific gravity
TDS	Total dissolved solids
USA	United States of America
WBCSD	*World Business Council for Sustainable Development*
WWF	World Wildlife Fund

1. INTRODUCTION

1.1 Terms of Reference

The terms of reference for this research project stem from the requirements of the University of the Witwatersrand, Faculty of Engineering and the Built Environment part-time programme of advanced courses and project work for the degree of Master of Science (Civil) in Geotechnical Engineering and Materials (50/50).

The field of research was selected after consultation with the School of Civil and Environmental Engineering Supervisor, Professor AB Fourie to investigate an area of tailings facility stewardship that has typically been neglected.

The primary aim of the research project is, after a thorough review of past and current techniques internationally, to develop guidelines and minimum requirements for successful closure. Specifically the objectives are to:

- Review and document closure techniques and their success or otherwise.
- Detail the factors that influence closure.
- Develop a set of guidelines and minimum requirements for success based upon learning.

1.2 Background Information

The mining industry has, and continues to produce millions of tonnes of metallurgical plant waste that has typically been disposed of on the earth's surface. Over time many innovative ways have been developed to facilitate this, but little regard has been paid to ensuring that the deposits are made acceptable in the longer term. Closure aspects have traditionally received minimal attention until the end of the mine's life when the deposits are hurriedly readied for abandonment. Tailings disposal typically represents one of the most significant environmental liabilities associated with mining operations.

Whilst the engineering and geotechnical principles involved with the design and construction of tailings facilities have been well developed in recent years, many attempts have been made, often on a trial-and-error basis, to ensure the long-term stability of tailings deposits. There however appears to be little evidence of lasting success to date.

Martin *et al* (2002) provide a good summary of historical environmental impacts that is worth repeating here as background to the issue: '*Around 1900, remote mining districts began to develop and attract supporting industries and community development. Conflicts developed*

over land and water use, particularly with agricultural interests. Accumulated tailings regularly plugged irrigation ditches and 'contaminated' downstream growing areas. Farmers began to notice lesser crop yields from tailings-impacted lands. Issues with land and water use that led to the initial conflicts led to lawyers discovering the fruitful field of mine waste management and litigation in both North America and Europe flourished. Legal precedents gradually brought an end to uncontrolled disposal of tailings in most of the western world, with a complete cessation of such practices occurring by about 1930. However, these practices still remain in many areas in the developing world where it is argued by proponents of such practices that this allows these jurisdictions to 'catch up' using the same environmental stewardship those in the western world practised the past two centuries.

To retain the ability to mine, industry fostered construction of some of the first dams to retain tailings. Early dams were often built across a stream channel with only limited provision for passing statistically infrequent floods. Consequently, as larger rainfalls occurred, few of these early in-stream dams survived. Minimal engineering or regulatory input was involved in the construction or operation of early dams.

Mechanized earth-moving equipment was not available to early dam builders. As a result, hand-labour construction procedure (the initial upstream method) was developed. A low, dyked impoundment was filled with hydraulically-deposited tailings, and then incrementally raised by constructing low berms above and behind the dyke of the previous level. This construction procedure, now almost always mechanized, remains at many mines today.

The first departure from the traditional upstream dam construction likely followed the failure of the Barahona tailings dam in Chile. During a large earthquake in 1928, the Barahona upstream-constructed dam failed, killing more than 50 people in the ensuing, catastrophic flow slide. The Barahona dam was replaced by a more stable downstream-raised dam, which used cyclones to procure coarser-sized material for dam construction from the tailings stream. By the 1940's, the availability of high-capacity earthmoving equipment, especially at open-pit mines, made it possible to construct tailings dam of compacted earthfill in a manner similar to conventional water dam construction practice (and with a corresponding higher degree of safety).

The development of tailings dam technology occurred on an empirical basis, geared largely to the constructed practices and equipment available at the time. This development was generally without the benefit of engineering design in the contemporary sense. Nonetheless, by the 1950's, many fundamental dam engineering principles were understood and applied

to tailings dams at a number of mines in North America. It was not until the 1960's however, that geotechnical engineering and related disciplines adopted, refined, and widely applied these empirical design rules. The 1965 earthquake-induced failures of several tailings dams in Chile received considerable attention and proved to be a key factor in early research into the phenomenon of liquefaction. Earthquake-induced liquefaction remains a key design consideration in tailings dam design.

Issues related to the environmental impacts from tailings dams were first seriously introduced in the 1970's in relation to uranium tailings. However, environmental issues related to mining had received attention for centuries. Public concerns about the effects of acid rock drainage (ARD) have existed for roughly 1.000 years in Norway. Public concerns were similarly expressed hundreds of years ago in Spain and in Greece. Mine workings developed in Roman times in Spain continue to produce ARD over 2.000 years later.'

The negative image of mining is not a recent phenomenon: '*The strongest argument of the detractors of mining is that the fields are devastated by mining operations…further, when the ores are washed, the waters used poisons the brooks and streams, and either destroys the fish or drives them away…thus it is clear to all that there is greater detriment from mining than the values of the metals which the mining produces.'* (Agricola, 1556).

Martin *et al* (2002) continue: '*in the early 1970's, most of the tailings dam structural issues (e.g. static and earthquake induced liquefaction of tailings, seepage phenomena and foundation stability) were fairly well understood and handled in designs. Probably the only significant geotechnical issue not recognised by most designers was the static load induced liquefaction (e.g. the reason for many previously 'unexplained' sudden failures). However, issues related to geochemical stability were not as well recognised, and tailings impoundments were rarely designed and operated with reclamation and closure in mind.*

Over the past 30 years, environmental issues have grown in importance as attention has largely turned from mine economics and physical stability of tailings impoundments to their potential chemical effects and contaminant transport mechanisms. Physical stability issues have remained at the forefront, as recent tailings dam failures have drawn unfortunate publicity to the mining industry, with severe financial implications in many cases (Davies, 2001). A significant tailings impoundment failure will almost certainly have a direct cost in the tens of millions of dollars and indirect costs, including devaluation of share equity, often many times the direct costs. In all of the tailings dam failure cases relatively simple, well-understood structural failure mechanisms were found to be at fault in causing failures.'

The advent of modern mining and milling techniques has resulted in the quantity of mining wastes increasing dramatically in recent times. Flotation and the use of cyanide for gold recovery significantly increased the ability to mine low-grade ore bodies resulting in larger quantities of finer tailings. With ever-increasing environmental pressures and higher standards being stipulated internationally, traditional practices are clearly unacceptable.

In conclusion therefore, there remain two significant issues that should be properly addressed by the mining industry, these being the stewardship (management) of tailings and reclamation (closure) of tailings storage facilities. This project considers the latter.

Key to the closure aspect is the concept of sustainable development. The Brundtland (1987) report, '*Our Common Future'*, submitted to the General Assembly of the United Nations, introduced the idea of sustainable development. The global approach defined sustainability as: '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'.

1.3 Scope of Research

This research considers the large volume residues emanating from common metallurgical processes and the associated tailings disposal techniques usually adopted by the mining industry. Specifically excluded are waste rock residues from mining activities and spent ore from the heap leach process although some case studies have been considered where this learning could be applied to tailings facilities.

The project offers the mining industry the following potential benefits:

- Improved planning and management of tailings facilities for closure through definition of successful methodologies.
- Improved ability to more accurately assess the future long-term behaviour of tailings facilities thereby facilitating adequate financial resource planning in relation to closure.

The outcomes of this research are:

- The production of a bibliography of important international technical papers, texts, guidelines and legal requirements relating to closure of tailings facilities.
- Compilation of case studies of examples of tailings facility closure practice.
- Development of key criteria for successful closure.
- Best practice closure guidelines or rules.

1.4 Process Used to Produce Guidelines

The first part of this report (Section 1 - Review of Current Practice) describes the methods used to dispose of the tailings, highlights the common problems associated with tailings facilities, outlines the state-of-the-practice in terms of closure, and describes special techniques. This information was provided to facilitate an understanding of the background and major issues and complications associated with the subject.

The second part of the report (Section 2 - Guidelines for Success) makes use of the outcomes of this work to produce tailings facility guidance and also examines potential strategies for success, key criteria for sustainable closure and methods of measuring success.

Numerous case studies used to derive the conclusions are summarised in the Appendix.

Relevant technical literature is listed at the end to assist with the definition of the factors that are important in ensuring success and for reference purposes.

2. REVIEW OF CURRENT PRACTICE

2.1 Tailings Disposal Methods

There are numerous texts and technical papers that cover the common methods of tailings disposal in detail, many of which are listed at the end of this report for reference purposes. A brief synopsis of the main methods is however presented in the following sections to provide an overview of current practice to assist with an understanding of the nature of the problem and to facilitate consideration of different approaches that would assist with ensuring successful closure. The described methods are categorised by environmental impact, rather than is more commonly the case by geotechnical technique.

Figure 2.1.1: Tailings deposition behind a cross-valley impoundment formed from mine waste material



2.1.1 Surface

Surface tailings disposal is the most common method as it is generally the only suitable option available as most mines are situated away from lakes, oceans, rivers and the mining schedule precludes the disposal of tailings below ground.

The philosophy that makes surface tailings disposal the solution normally adopted is that it is preferable to store tailings on the surface and above the ground water table where potential negative impacts can be managed.

Figure 2.1.2: Tailings deposition behind a ring-dyke formed from the coarse tailings fraction



The conventional approach is to build confining perimeter impoundment walls in valleys or flat areas to create a basin to receive the slurry. The tailings material is typically transported as slurry that contains large quantities of water and is discharged from the ore processing plant into the basin where the solid fraction settles out into a loose structure until consolidation takes place. The main reason for the high water content is that most metallurgical processes rely upon water and it has been substantially cheaper to transport the tailings as slurry.

Figure 2.1.3: Tailings disposal via spigot deposition



Many different methods have been developed to contain the tailings material. These methods include use of the tailings material to form the impoundment walls via the use of hydro-cyclones, or particle segregation by gravity along the beach with spigot deposition, or the use of solar evaporation to achieve consolidation of a perimeter wall, as practiced in South Africa. Selection of the technique is dependent upon the nature of the tailings material and the site conditions.

Figure 2.1.4: Filter cake disposal via conveyor in arid climate



More recently efforts have been concentrated upon the discharge of less water to the environment for many reasons with the result that tailings material is sometime transported to the facility using positive displacement pumps or by conveyors.

Co-disposal techniques are practiced in some instances where the finer tailings is disposed of with coarser mine waste either simultaneously or separately using the coarse material to impound the finer tailings.

Figure 2.1.5: Co-disposal of colliery slimes and discards



Surface tailings disposal has a number of drawbacks however: these are discussed in the next section. The chief problem with surface deposition is that since ultimately all materials decompose, erode and are transported to the oceans in geological time, it is very difficult to achieve a sustainable closure solution for surface tailings disposal facilities.

2.1.2 Riverine

Riverine tailings disposal is the disposal of tailings slurry into a river. This practice continues in certain locations of the world such as Papua Guinea at Porgera and Indonesia at Grasberg (MMSD, 2002c and 2002d). Pressure groups have influenced regulators and lending sources to the extent that the practice is now becoming rare and elicits significant outcry where it continues. An example of this is Ok Tedi in Papua Guinea where, despite regulatory approval for riverine tailings disposal, the owners have disposed of their shareholding as a result of adverse international reaction (BHP Billiton 2004a). BHP Billiton has subsequently publicly stated that it would no longer invest in new projects using riverine tailing disposal and capital review processes are to include a requirement for vigorous social and environmental assessments from the outset (BHP Billiton 2004b).

Figure 2.1.6: Porgera riverine disposal, Papua New Guinea

(ref. **http://mediaearthworksaction.org**)



Riverine tailings disposal is no longer considered acceptable by public pressure groups, including the World Wildlife Fund, for reasons of unacceptable water pollution, wildlife mortality and disturbance and impact on human life.

Two types of riverine disposal can be differentiated. In some instances the river is used to transport the slurry downstream of the metallurgical plant for disposal within a facility at a more suitable location, as takes place at Grasberg. This is often the case where the terrain is mountainous such as in the high Andes in South America, Papua Guinea or Indonesia. In some instances the river is used to transport the slurry and deposition occurs naturally along the river or only when the river enters the ocean, as at Ok Tedi.

Potentially adverse environmental impacts include sedimentation, deterioration of water quality, damage to biodiversity and negative impacts upon communities.

Riverine tailings disposal is prohibited in the United States, Canada, Peru and elsewhere.

2.1.3 Lake and submarine

Lake and submarine (sub-aqueous) tailings disposal are considered to be a viable method of eliminating air to minimise the oxidation of sulphides to prevent ARD within some tailings materials, since reactive tailings can have a stable geochemistry under water. Other advantages are that engineering structures are minimised resulting in a low-cost closure and maintenance system with a low risk of failure in the long-term.

Submarine tailings disposal is practiced in a number of locations around the world such as Lihir Island, Papua Guinea and was, until recently in Peru but has now been banned. The practice is also severely restricted in places such as the United States of America and Canada to the extent that no mine has qualified to dispose of tailings in the ocean since regulations were promulgated.

The feasibility of submarine tailings disposal is almost entirely dependent upon specific circumstances and upon extensive analyses that include physical, chemical and geological oceanography and sedimentation characteristics. Submarine tailings disposal should only be practiced when the correct combination of conditions render the potential environmental impacts minimal. These conditions should include (Bauer *et al*, 1995):

- Milling does not liberate secondary toxic products.
- There are no readily dissolvable toxic substances.
- No toxic reagents are used in the metallurgical process.
- Slurry is deposited with minimal amounts of water to minimise submarine transportation.
- Tailings are de-aerated before discharge.
- The density of the slurry is equal to water density at the depth of disposal.
- Tailings outfall is placed effectively.
- The receiving environment is stable.

Public pressure groups state that the impact of submarine disposal is not well known, there is very little research available as to the long-term effects of this method on tropical marine areas, and that the available science comes from the mining companies without long-term independent research (WWF, 2004). BHP Billiton has committed to not pursuing deep sea tailings disposal for any of its current prospects and believes that it is unlikely that the technology would be pursued in any future developments (BHP Billiton, 2004).

Clearly careful analysis of potential environmental impacts is required for lake or ocean deposition. The Precautionary Principle should apply in cases where there is inadequate data or knowledge to demonstrate that the practice is appropriate in the circumstances.

Lake or marine discharges of tailings should only be undertaken after:

- A thorough environmental analysis of alternatives has been conducted.
- The potential effects on marine resources are fully understood.
- It has been demonstrated that a significant adverse effect on coastal resources should not result.

2.1.4 Underground

Underground tailings disposal can prove viable for some of the tailings produced. It must however be realised that, because of the bulking of the ore upon excavation and processing, not all tailings could be accommodated underground. Furthermore this method is not necessarily cheap given the complexities associated with placing the material underground safely and recovering water for re-use in the metallurgical plant. The mining schedule and ore sterilisation often preclude this method.

Figure 2.1.7: In-pit tailings disposal



There are however significant potential advantages with this method. In open pit mines the use of tailings material to backfill the void decreases the closure costs associated with the tailings material at the same time as pit remediation. In underground mines the tailings material can be used, after treatment, for support purposes. Tailings material for underground support is preferable to the traditional materials such as timber roof supports, which are prone to spontaneous combustion. Hydraulic backfill and cemented paste are made from the tailings material.

Pit or underground hydro-geology is perhaps the most important consideration in determining the potential for this method: the hydro-geological conditions should be fully understood.

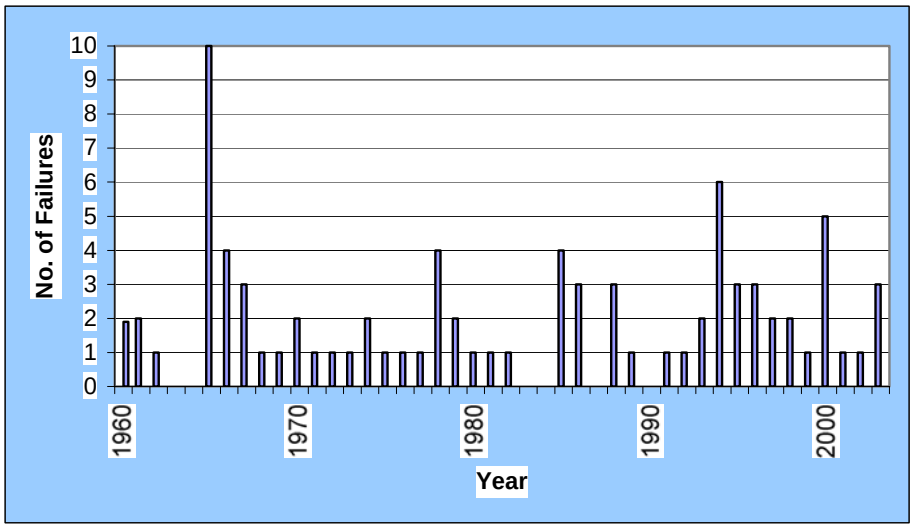
2.2 Problems Associated with Tailings Facilities

Tailings facilities as currently normally constructed have the potential to cause many different problems during both the operational and post-closure phases. Some of the main problems associated with tailings facilities are discussed briefly in the following sections and include impoundment failures, dust generation, erosion and water contamination.

2.2.1 Impoundment failures

The most dramatic problem associated with most types of tailings facilities is that of sudden geotechnical failure usually caused by impoundment failure via slope instability, over-topping or similar mechanisms usually associated with water and mismanagement.

Figure 2.2.1: Number of recorded tailings facility failures since 1960 (Antenna 2004)



Critical issues associated with tailings facilities are that:

- They are typically constructed in stages or on a continuous basis over many years by different teams. As a result, the condition of the facility constantly changes. Safety and stability issues must therefore be continually re-evaluated.
- Mine operators have the chief responsibility of extracting minerals from the ground. They are also typically responsible for residue facilities with the result that facility management is a secondary function.
- Problems that may develop with a facility can often take many years to manifest, which can lead to masked stability issues and complacency towards mitigation.
- Poor design and operational standards have been accepted where facilities are viewed as an unprofitable, money-draining part of the mining and processing operations.

- Facilities have a long-term closure phase as well as an operational phase. They have to be designed and constructed to be stable and durable indefinitely. Some degree of surveillance and maintenance long after the mining activities have ceased will be required.
- Closure configurations and activities must be considered upfront.

Tailings facility failures have unfortunately been regular occurrences ever since the mining industry moved away from the discharge of waste to stream and built impoundments to lessen the environmental impacts. Figure 2.2.1 depicts the number of recorded tailings facility failures over the last forty-three years providing an indication of the estimated failure rate of the approximately 3.500 tailings facilities worldwide (Davies, 2001). It is worth noting that the number of recorded failures is substantially less than the actual failure rate as most go unrecorded: some estimates indicate a rate of five-fold the reported frequency.

Figure 2.2.2: Slope failures of a ring dyke slimes dam in South Africa



Tailings facility failures can result in significant adverse social and environmental impact as well as affecting the financial viability of the mining company and its owners.

Figure 2.2.3: Merriespruit slimes dam failure in 1994



Figures 2.2.2 to 2.2.4 illustrate some tailings facilities failures.

Figure 2.2.2 shows the slope failures that occurred within the impoundment walls of a ring dyke slimes dam in South Africa in 1993 triggered by a rapid rise rate.

Figure 2.2.3 shows the effects of slime and water that escaped from the Merriespruit slimes dam in South Africa in 1994. The failure, which claimed seventeen lives in the downstream suburb, was the result of water mismanagement on a dormant facility.

Figure 2.2.4: Colliery washing plant pond failure

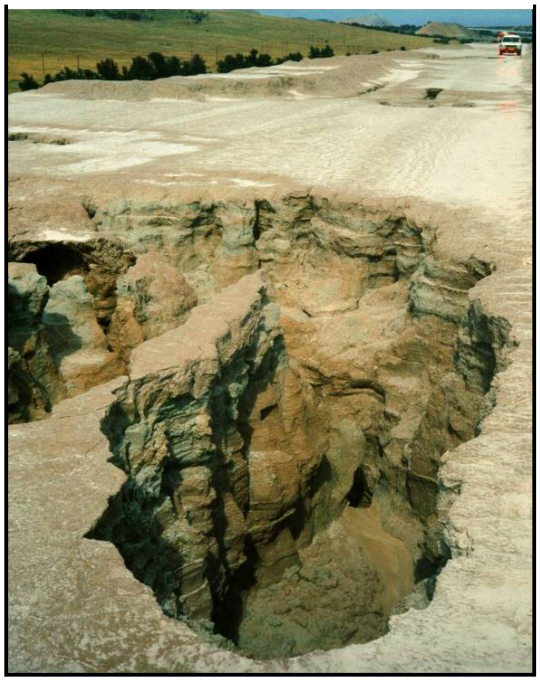


Figure 2.2.4 shows a spill from a colliery washing plant pond in South Africa that burst its impoundment wall allowing the escape of slimes into nearby watercourse which carried material for tens of kilometres.

2.2.2 Dust

Dust generation is a problem in drier climates and typically where the tailings surface is exposed. The dust generated from the tailings facility can be harmful to human health, may damage crops and vegetation, or may be a nuisance.

Figure 2.2.5: Erosion caused by water ingress



2.2.3 Erosion

Erosion of the surfaces of a tailings facility is a significant problem that is difficult and expensive to remediate and prevent. Although erosion is a major problem during the operational phase, it is especially damaging after closure when substantially less maintenance is provided and there are typically fewer resources available.

Unless properly closed, erosive forces will eventually destroy the integrity of the facility and will exacerbate other adverse environmental impacts.

Rates of erosion in the order of 500t/ha/year have been measured on the slopes of tailings facilities where the slopes have been formed from the tailings material (Blight, 1989).

2.2.4 Water contamination

ARD is a major problem that could affect surface and ground water in the vicinity of tailings material deposited on surface. Exposure to air and water results in oxygen that produces many chemicals such as sulphuric acid which in turn react to produce toxic, acidic waters containing heavy metals. Contamination by such leachate has caused severe environmental degradation in many mining areas.

Figure 2.2.6: Aerial view of slimes dam showing sinkhole

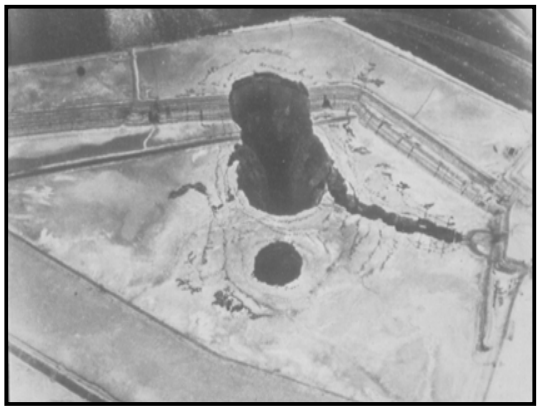


Figure 2.2.6 is an aerial view of a slimes dam in the Far West Rand showing large sinkhole formation associated with dolomitic limestone foundation.

Figure 2.2.7 shows acid seepage at the toe of a tailings facility.

Figure 2.2.7: ARD at the toe of a tailings facility



2.3 Closure Drivers

It is necessary to understand the factors that influence the closure process before undertaking closure activities. Historically mining companies have typically focused upon the legal and financial aspects, placing lesser emphasis upon the environmental and social aspects.

With the relatively recent focus upon sustainable development, the new closure drivers are ensuring economic viability, ecological integrity and social equity. Today's key drivers are therefore in the legal, environmental, financial and social fields, with a more equitable importance being required for each. No company can afford to ignore any one.

2.3.1 Legislation, regulations and guidelines

Mine closure should be undertaken because regulators and industry are focusing on mine closure issues, regulatory instruments are being used to impose legal obligations and codes of practice are being formulated that may have legal consequences. Regulators are setting and enforcing increasingly stringent legislation chiefly as a result of increased pressures from society. With the massive impact of information technology and the media in the 'global village', tremendous pressure can and is applied to 'right wrongs' and expose those who are believed to be conducting their affairs to the detriment of others.

Whilst it is clear that mining companies must comply with legislation and regulations or else face sanction or penalty, the role and impact of guidelines should be considered. Many believe that adherence to guidelines is optional. Guidelines however imply some sort of legal obligation as, if one has followed such guidance, the defence that industry best practice has been followed could be used. Where such guidance has not been adopted this defence cannot be used and the alternative measures should instead be based upon science and research.

2.3.2 Environmental and social

A current view (Golder Associates, 2003a) is that possibly the only true measure of sustainable development is quality of life, which is affected by many factors derived from the Hierarchy of Needs (Maslow, 1954) such as:

- Improved biophysical environment.
- Improved health and life expectancy.
- Increased wealth and buying power.
- Increased sense of security.

- A feeling of freedom.
- The potential to grow, develop and be mobile.
- Improved social acceptance, influence and recognition.

Mining can influence many of these factors, not only during the operational life of the mine but beyond closure.

Development that improves quality of life indefinitely into the future is therefore sustainable. In the words of AngloGold Ashanti's Chief Executive Officer, Bobby Godsell: 'The place should be better off for our having been there.' (Godsell, 2004).

2.3.3 Financial

The key driver in mine closure for a mining company is that of limiting liabilities. Most liabilities and mitigation thereof, can be and are translated into financial terms that either negatively or positively affects the financial performance of the enterprise. From a business perspective there is often strong desire to defer expenditure as far into the future as possible, as money spent early in a project's life will typically have the greatest affect on net present value (NPV) calculations and hence project rewards. Obviously there is a significant risk with this approach that the mining company that defers rehabilitation work to the end of its life might well not be able to afford the necessary work or may have ceased to be in business. Many nations therefore require guarantees that make adequate provision for deferred work.

The mining industry typically views the provision of financial guarantees as being an economically sensitive issue since they bind substantial amounts of money for long periods, which locks up capital hampering new investment. For this reason regulatory authorities should endeavour to guarantee the correct closure and post-closure environmental performance of mines without transferring significant costs to society.

Financial guarantees

Financial assurance policies relating to closure are required by many nations. Financial securities can be in the form of financial provisions to confirm the financial soundness of the company, corporate guarantees, cash deposit, or an irrevocable letter of credit or reclamation fund for example.

Financial burden

The financial burden on mining companies can be divided into direct costs, in the form of fees associated with third party security, legal and administration costs *et cetera,* and indirect

costs caused by the reduction of the companies borrowing capacity and an increase in cost of loans (Miller, 1998).

The European Commission intends to make financial guarantees for mine closure mandatory and intends to demand a financial deposit or other equivalent means, readily available for the rehabilitation of land affected by mining waste management facilities. The deposit is proposed to be calculated and weighted according to the degree of environmental threat posed and the future use of the rehabilitated land. In active operations, any authorisation to construct a facility is planned to be conditional upon the prior establishment of a guarantee by the operator.

Amongst the countries where some form of financial surety for mine closure is used are Canada, the United States, Australia, Indonesia, Japan and South Africa. Various forms of surety are normally accepted within each country. Typically the amount of the surety is derived through consensus discussions between the company, the authorities and third party insurers, from the cost estimated by the mining company based on the developed closure plan. The financial guarantee is typically revised at certain intervals and adjusted to the actual conditions and any developments of the closure plan.

After closure works have been finalised the guarantee is normally released following the inspection of the competent authorities, with the possible exception of a small retention to guarantee any additional remedial measures or follow-up.

An important factor that influences the burden of the financial guarantee is the tax arrangements in place. Tax arrangements vary between countries but it is usual that all costs related to the financial guarantee are tax deductible from the profits of the operation.

Issues in the use of financial guarantees

There are many issues in the use of financial guarantees for mine closure and after-care.

Need and size

Evaluation of the need for and the extent of a financial guarantee are difficult exercises. The choice should depend on factors such as policy, company financial records, size of company, and should be site specific considering such factors as the need for long-term care.

Existing and extended, new and old sites, abandoned sites

Requirements for financial guarantees for mine closure can only be imposed for new mines as existing mines often cannot cope with additional guarantees for existing or old sites for financial reasons. Special rules are required for existing operations as they cannot readily change existing mine design and therefore cannot adapt readily to new financial requirements.

In the case of extension, the requirement of certain guarantees could result in the need for double of the original investment amount, which given the current earnings of the mining industry would not be feasible. The impact, however, would not only be that the mining operations cannot expand, but that they will have to close since they cannot compete on the world market any longer due to lesser ore quality or no further access to the ore.

Already abandoned sites obviously cannot be covered by financial guarantees.

Determination of after-use

The need for and the size of any guarantee should depend on the agreed and approved closure and rehabilitation plan as well as the ultimate land use. This agreement should have been established on the basis of stakeholder consultations and negotiations, which could differ substantially from mine to mine. Similarly technologies applied and required costs would differ depending on geology, employment and other conditions.

Legal framework

The necessary framework and competence to supervise the review and approval of company closure plans, negotiation and revision of guarantees and the approval of closure works need to be in place with the authorities.

Competitiveness

To maintain competitiveness it is important for a mining operation that:

- A financial guarantee only is provided from the beginning of the operation and not at the beginning of the application for a permit.
- It should be able to adjust, in agreement with the authorities, the size of the financial guarantee to the type and size of the operation and the land use.
- It should be faced with legally defined and enacted procedures for the assessment, establishing, evaluation and reviewing as well as the release of any such guarantees.

The tax arrangements around financial guarantees are important to compensate the companies for the cost implications resulting from the introduction of guarantees.

Incentives for improvement and reduction of financial burdens

Society's pressure on performance is high. Today, law, loss of image, loss of capital and reduced access to financial and other resources punishes inappropriate performance.

Financial guarantees could be reduced based on company track records of success. This could be established on the ability of the company to show cases where the company has voluntarily closed mines to an acceptable standard.

2.4 State-of-the-Practice

2.4.1 Legislation, guidance and best practice

Mining companies

Mining companies, particularly the larger ones, are increasingly developing company or corporate policies and procedures that encompass residue management in one form or another at least in the form of broad, generic environmental policy statements. Few companies appear to have detailed or published requirements. Some examples of commitments made are described below.

A large London-based mining company recommends that its operations adhere to best practice principles that include commitment to complete life-cycle management and decommissioning and closure of tailings facilities to protect human health and the environment. Closure planning is recommended during the feasibility and conceptual stages with subsequent review and update. Rehabilitation trials and preparations for closure are to be undertaken during the operational phase. Aftercare and post-rehabilitation monitoring requirements are outlined. Stakeholder communication is encouraged.

AngloGold Ashanti Ltd has a tailings management framework to cover all aspects of tailings disposal through the complete life-cycle (Robins, 2004). The framework comprises a set of principles with minimum standards of practice and supporting guidance. Closure is covered by the following standards of practice:

- Close the tailings facility properly to ensure a sustainable solution in accordance with planned tailings facility land use.
- Adopt a 'design for the environment' approach to tailings facility design.
- Establish environmental baselines and analogue sites.

- Re-evaluate tailings facility-related risks that may be present upon cessation of operations.
- Develop site-specific closure criteria.
- Prepare a detailed final closure plan.
- Plan and implement procedures to manage storm water run-off and solutions from the tailings facility with the objective of protecting human health and the environment.
- Control releases of potential pollutants from closed tailings facilities to protect human health and the environment.
- Provide financial assurance for the closure of tailings facilities within mine rehabilitation planning activities consistent with political jurisdictional requirements.
- Implement a monitoring and aftercare programme to confirm that procedures and controls are effective.
- Conduct transparent reporting.

Barrick's corporate goals with respect to tailings facility closure are (Espell *et al*, 2004):

- Design the closure process such that the tailings are chemically and physically stable, under current and anticipated closure standards of performance.
- Maintain hydraulic separation between the tailings mass and the underlying/nearby surface and groundwater resources.
- Return the area to a viable post-mining land-use.
- Achieve closure within a minimum time frame.
- Limit long-term environmental liability to the company, the State, and other affected parties.

BHP Billiton follows management standards that form the basis of company management systems at all levels (BHP Billiton, 2004b). The standards cover the entire life-cycle of operations including decommissioning, closure and rehabilitation. A strong emphasis is placed upon risk assessment. BHP Billiton requires that closure, decommissioning, remediation and rehabilitation plans are established, fully costed, documented and annually reviewed.

Newmont considers that closure and reclamation of mining operations provide an opportunity to create a positive legacy for host communities (Newmont, 2004). Newmont's closure principles (Slight and Lamont, 2004) involve subscription to the following:

- Newmont values.
- Nature as a stakeholder.

- Benchmarking.
- Partnerships and people.
- Adding value.
- Plan-act-verify-monitor.
- Pride.

An Australian resources company manages tailings, heap leach and water storage facilities via a set of management system guidelines, which cover the design and operation aspects. A tailings management master plan is required to be prepared. The guidelines advocate:

- All aspects of the design must be carried out with the view to facilitating and simplifying the safe, environmentally acceptable and cost effective decommissioning and closure of the facility.
- Significant monitoring throughout the operation to confirm that the facility is performing according to the design assumptions to facilitate the development of the detailed closure plan.
- Stripping and stockpiling of topsoil.
- Progressive rehabilitation.

Mining industry organisations

Minerals Council of Australia/Ministerial Council on Mineral and Petroleum Resources

The Minerals Council of Australia and the Ministerial Council on Mineral and Petroleum Resources have jointly prepared a strategic framework for tailings management (Minerals Council of Australia and Ministerial Council on Mineral and Petroleum Resources, 2003).

The framework recommends that all man-made structures should be physically and chemically stable presenting no hazard to public health and safety or the environment, as a result of failure or deterioration. The following objectives, which are repeated in the Environmental Protection Agency's best practice environmental management in mining guidelines (EPA, 1995), are stated:

- Containment/encapsulation of tailings to prevent leaching into ground and surface waters.
- Provision of surface drainage and erosion protection to prevent surface water transporting tailings from the storage area.
- Provision of a stabilised surface cover to prevent wind erosion.
- Design of closure to minimise post-closure maintenance.

The following are also recommended:

- Ensure closure planning is an integral component of project development, design and operations.
- Minimise the potential environmental impacts of decommissioned tailings facilities by designing for long-term stability.
- Ensure that an effective monitoring programme is in place to demonstrate that the agreed completion criteria have been achieved.

Mining Association of Canada (MAC)

The Mining Association of Canada has produced two documents that relate to tailings facilities: essentially guides to the management of tailings facilities and developing an operations manual (MAC, 1998 and MAC, 2002). Key components of the recommended framework are checking and corrective action, as well as management review for continual improvement. A checklist for decommissioning and closing a tailings facility is included.

International Committee on Large Dams (ICOLD) and Related Organisations

ICOLD has produced many guidelines that relate to the design and operation of tailings facilities (see Appendix) with one dealing with closure aspects in some detail (ICOLD,1996).

International Council on Mining and Metals (ICMM) - (Formerly International Council on Metals and the Environment (ICME))

The ICMM produced the following ten principles for sustainable development (ICMM, 2003):

1. '*Implement and maintain ethical business practices and sound systems of corporate governance.*
2. *Integrate sustainable development considerations within the corporate decision-making process.*
3. *Uphold fundamental human rights and respect cultures, customs and values in dealing with employees and others who are affected by our activities.*
4. *Implement risk management strategies based on valid data and sound science.*
5. *Seek continual improvement of our health and safety performance.*
6. *Seek continual improvement of our environmental performance.*
7. *Contribute to conservation of biodiversity and integrated approaches to land use planning.*
8. *Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products*.
9. *Contribute to the social, economical and institutional development of the communities in which we operate.*

10. *Implement effective and transparent engagement, communication and independently verified reporting arrangement with our shareholders*.'

The ICMM is currently developing a best practice web site that is meant to assist the industry with tailings-related issues.

International Institute for Environment and Development (IIED) and World Business Council for Sustainable Development (WBCSD)

Mine closure is covered in some detail in the IIED/WBCSD working paper (MMSD, 2002d). Specific requirements relating to tailings facilities are tabulated to provide information on closure considerations (Table 2.4.1).

Table 2.4.1: Closure considerations for tailings facilities (MMSD, 2002d)

Issues	Objectives	Control
Physical stability • Dust • Erosion • Dam wall • Drainage	• Stable structures • Avoid failures & slumps • Control sediment	• Site selection • Dam design • Tailings disposal method • Cap & vegetate • Control drainage
Chemical stability • Metal leaching • Acid drainage • Mill reagents • Dam structure	• Clean water (surface & ground water) by: - Control reactions - Control migration - Collect & treat	• Use chemically stable material in dam wall construction • Pre-treatment of tailings • Cover to control reactions • Form wetland • Divert run-off • Collect & treat effluent • Monitor
Land use • Productivity • Visual impacts	• Restore to appropriate land use	• Re-contour, cap & establish vegetation • Flood & form wetland

Chamber of Mines of South Africa (COMSA)

Research on tailings dams was carried out at the National Building Research Institute in the early 1950's. In 1970's the South African mining industry and the environmental governmental agencies first prepared guidelines for environmental protection (COMSA, 1979a). These guidelines were most recently revised in 1995 and cover the design, operation and closure of base and precious metals, diamond and coal residue deposits. The guidelines are in the form of a technical document that primarily addresses the geotechnical engineering issues of residue disposal. The philosophy of voluntary protection of the environment adopted by the document is that of BATNEEC (the application of Best Available Technology Not Entailing Excessive Cost).

The Chamber published separate guidance to cover the stabilization and protection of the surface of tailings facilities by means of vegetation (COMSA, 1979b).

Regulatory authorities

Northern Territory of Australia

The broad objective for mine closure in Northern Territory is that mine sites should be rehabilitated to a standard which minimises or negates restrictions on sequential land use both on the site and adjacent areas (DME, 1997). Key requirements are:

- Compatibility with agreed post-mining land use.
- Physical safety.
- Low risk to biota.
- Stability.
- Rubbish clean-up.
- Revegetated or otherwise improved.
- Visual amenity preferably compatible with adjacent landscape.
- Protection of heritage and archaeological sites.

South Africa

Tailings disposal is essentially covered under South Africa legislation through the requirement to produce a mandatory code of practice (DME, 2000) which invokes the requirements of the SABS Code of Practice (SABS, 1998).

The code requires that a closure report be prepared that details the nature of the decommissioning works, confirms structural stability and outlines the probable or recommended extent of ongoing maintenance required to sustain the facility at acceptable levels in accordance with potential hazard and impact.

A decommissioning and aftercare report should be prepared that contains the following:

- Safety and environmental classifications.
- Decommissioning aims.
- Final land-use or capability.
- Conceptual description and details for decommissioning and aftercare works.
- Cost estimates for the works and operational resources and means of funding the plan.
- Residual impacts, monitoring programme and conditions that should be fulfilled to qualify for closure in terms of the law.

The plan should:

- Provide sufficient detail to allow for detailed planning and design to proceed and to facilitate its implementation.
- Be prepared in consultation with interested and affected parties.
- Be prepared in consultation with the persons or parties who will assume responsibility for aftercare.

Western Australia

Guidelines for mining in arid environment produced by the Department of Minerals and Energy in Western Australia contain technical details of rehabilitation that could be applied to tailings facilities (DME, 1996).

The DME requires that decommissioned tailings facilities must be safe, stable and aesthetically acceptable (DME, 1999).

Financial institutions

International Finance Corporation (IFC) - A Branch of the World Bank

IFC guidelines on precious metals mining have been drafted and circulated for comment prior to implementation (IFC, 2004). The draft guidelines focus upon pollution control and recommend:

- Concurrent reclamation during the operating life of the mine.
- Consideration of new beneficial land uses based on changed conditions at the site as well as alternative uses by local communities or other industries.
- Discouraging or limiting access post-closure in certain circumstances.
- Rehabilitation of hydrological regimes to the extent feasible.
- Re-application of a growth medium with a total thickness of not less than prevailing in un-mined areas although direct vegetation of tailings may be acceptable.
- Rehabilitation trials.
- Incorporate appropriate aftercare and monitoring for three years or longer if required.
- Contingency planning that covers possibility of temporary suspension of activities and permanent early closure.
- Full funding by appropriate financial instruments.

Pressure groups consider the current guidelines on tailings and waste rock disposal to be ‘extremely general’ (Whirled Bank, 2004).

European Union

The European Commission has tabled a draft reference document on tailings and waste management (European Commission, 2004). The document includes a review of techniques to consider in the determination of best available technology (BAT), best available techniques and emerging techniques for the management of tailings and waste rock in mining activities.

Recommended elements of a closure plan include:

- Determination of background data including site history, infrastructure, process flow controls, system operations, mineralogy and topography.
- Hydrology and water management.
- Hydrogeology.
- Soil capability.
- Re-vegetation.
- Impact assessment.
- Long-term maintenance.
- Geotechnics.
- Chemistry and geochemistry.
- Monitoring programme.
- Effluent management or treatment requirements.
- Communications.
- Financial assurance.
- Stakeholder consultation.
- Potential end land use.
- Closure technology (dry or wet cover, flooded, wetlands, perpetual treatment or vegetative cover).

The closure plan should:

- Include closure costs in the assessment of alternatives.
- Adopt a risk assessment approach.
- Be maintained throughout the active life of the facility and routinely updated taking into account any modifications to the design and during operation.
- Encourage facility design to facilitate premature closure if necessary.
- Minimise the need for active aftercare management.

Long-term closure objectives should ensure physical, chemical and biological stability.

Best available technology with respect to closure is considered to be to develop closure and aftercare plans during the planning phase, including costs estimates, and then to update them over time.

Consulting organisations

Consulting organisations that specialise and operate in the field of tailings facility design and closure include:

AMEC http://www.amec.com

Australian Tailings Design Consultants http://www.mpaw.com.au

GHD http://www.ghd.com.au

Golder Associates http://www.golder.com

Jones & Wagener http://www.jaws.co.za

Knight Piésold Consulting http://www.knightpiesold.com

Metago Environmental Engineers (Pty) Ltd http://www.metago.com

Robertson GeoConsultants Inc. http://www.robertsongeoconsultants.com

Coffey/Soil & Rock http://coffeygeosciences.com.au

SRK Consulting http://www.srk.com

URS Consultants http://www.urscorp.com

The organisations have developed internal procedures and techniques that assist the closure design process. Generally however the consultant would apply local regulations and experience, whilst endeavouring to accommodate the client's wishes and budget.

Some of the closure philosophies and techniques used and developed by such firms are discussed in section 3.3.10 (Design process).

2.4.2 Selected case studies

The case studies considered as part of this review are summarised in the Appendix. The key learning points are listed below:

- Alleviation of one problem often causes others.
- Although pasture grassing of steep slopes contributes to temporary dust control, the grass requires intensive irrigation and fertilisation for establishment, requires continual maintenance, lacks persistence, regenerates poorly (by seed) and contributes little to erosion control.

- Any disturbance to the natural slopes, for example formation of tracks, roads or borrow-pits, quickly results in severe erosion.
- Balanced cut-to-fill minimises cost of earthworks.
- Benefits associated with the reduction of slope angles.
- Benefits of holistic management principles and practice.
- Benefits of removal of potential pollutants from bulk of the tailings material and concentration for disposal in fully lined facilities.
- Closure of the tailings impoundment is not possible until the natural slopes upstream have been stabilised.
- Commence rehabilitation activities during operational phase wherever possible.
- Compacted earth fill to form impoundment walls is more resistant to erosion that tailings material.
- Conduct rehabilitation trials as soon as possible.
- Conversion of arsenic at plant into potentially less harmful oxidation state.
- Cycloned underflow erodes readily because of its uniform grading and must therefore be stabilised soon after deposition.
- Dewatering and deposition method produce an end-product that has natural slopes that should be more amenable to closure.
- Difficulties of protecting slopes where vegetation establishment is not a viable solution to slope stabilisation.
- Difficulties of working in extremely hot environments.
- Difficulty and expense of seepage management during and after tailings facility closure.
- Dust from salt crystallisation on surface of tailings could be a problem for surrounding vegetation.
- Early results from rehabilitation trials could be misleading in that moisture conditions on the tailings facility are typically different to the situation long after decommissioning.
- Ease of vegetation establishment in amenable climatic zone.
- Face erosion can sometimes be minimal despite steep profile where there is good vegetation cover and storm water drainage measures.
- Flatter slopes are more readily rehabilitated.
- Generation of hyper-saline process water through evaporation and problems associated with scaling of pipes and the unsuitability of the use of this water in the metallurgical process.
- Grass establishment during operational life significantly reduces maintenance.
- High capital cost associated with dewatering and pumping high density materials.
- Importance of allowing for settlements of tailings in closure design.

- Importance of assessing full life-cycle costs of tailings deposit including those associated with closure and after-care.
- Importance of creating a natural environment in keeping with surroundings.
- Importance of creating the correct geometry for storm water control prior to vegetation establishment.
- Importance of ensuring good vegetation cover at the crest of the impoundment wall to minimise wind erosion and dust generation.
- Importance of ensuring that storm water drainage details and earthworks have been properly conducted prior to commencing vegetation establishment.
- Importance of good storm water management engineering details.
- Importance of minimising water storage on the tailings facility to limit environmental issues (seepage) and to maximise capacity (reduce the need for expensive raises).
- Importance of planning deposition to minimise the amount and cost of closure.
- Importance of water conservation in arid areas.
- Initial capital costs are high with the North American approach but long-term liabilities are substantially reduced.
- Innovative use of grass mats for vegetation establishment.
- Introduction of organic matter (compost, litter) and physical and chemical heterogeneity to slopes (i.e. textural soil classes, gravels, textural vegetation).
- Introduction of tolerant micro-organisms.
- Large footprint to rehabilitate in the case of a Central Thickened Discharge (CTD) facility.
- Long-term consolidation of tailings and associated problems with final capping.
- Low energy facility in the case of a CTD.
- Must demonstrate the long-term performance of innovative ideas.
- Naturally-selected plants and micro-organisms can grow well in slimes.
- Need to allow for long-term consolidation of tailings especially in filled pits.
- Need to cut vegetation during operational life to facilitate inspection.
- North American approach is to apply highest available standards to facilitate permitting process.
- Pasture grassing of steep slimes dam slopes is not ecologically or economically sustainable.
- Poor rehabilitation results in cases where the focus has only been on vegetation establishment and not on ensuring the correct storm water management measures are in place first.
- Potential for thickened tailings material to be used to backfill open pits for closure.
- Proper erosion control measures especially on the outer face of the impoundment wall.

- Proximity of tailings facility to human habitation necessitates a strong emphasis on social issues and stakeholder participation.
- Rapid deterioration of tailings facilities after decommissioning where rehabilitation works have not been successfully concluded.
- Rapid erosion of loosely stacked heap leach material.
- Severe problems require concerted efforts and long-term commitment to rectify.
- Some tailings materials are relatively inert because of metallurgical process and therefore support vegetation growth.
- Some trees and other plants which grow well in slimes are commercially valuable and could form the basis of rehabilitation industries on the goldfields.
- Storm water management is extremely important.
- Sub-aerial deposition provides a cost-effective method by increasing tailings density.
- Sub-aerial deposition results in tailings mass amenable to grading and reclamation.
- The dominant naturally-colonising and persistent vegetation of gold slimes dams in South Africa is indigenous, perennial, woody and semi-woody.
- There exist a range of indigenous and some exotic woody species (forbs, shrubs and trees) extremely tolerant of growth in acid and saline slimes and that maintain productivity and viable seed production equivalent to conspecifics in unpolluted veldt.
- Trespassing can be difficult to control.
- Underflow material is highly susceptible to erosion and vegetation does not adequately bind this material.
- Use of disused pits to dispose of tailings whilst closing pits.
- Use of filter cake to rehabilitate disused open pit.
- Use of local sub-contractors to assist with rehabilitation efforts.
- Use of tailings slurry to backfill exhausted open-pits as part of reclamation plan.
- Use of thickened tailings to change basin profile from sloping upstream to sloping downstream thereby maximising capacity.
- Use of thickened tailings to rehabilitate old slimes dams whilst maximising capacity.
- Value of coarse tailings fraction for underground stabilisation purposes.
- Value of enthusiastic and dedicated team.
- Value of field tests.
- Value of focussed rehabilitation efforts.
- Value of strategic plans developed in conjunction with regulators and that encompasses areas greater than a single mine site.
- Waste overburden material can be used to successfully rehabilitate tailings surfaces.
- Waste rock material often is relatively well graded and is therefore less prone to erosion.

2.5 Special Techniques

2.5.1 Clean metallurgy

Clean production is becoming increasingly important. This requires an integrated design approach commencing with the start of metallurgical process right through to facility and not merely with design from the end of pipe at the tailings facility as has been the normal practice.

There is often considerably more latitude available to the design of metallurgical processes than the geotechnical engineer/tailings designer realise. Financial factors usually strongly influence the selection of the metallurgical process. Within reason however it is often possible to manipulate the design during the conceptual stage of a project to produce a waste or tailings material that is substantially more amenable to dispose of in an environmentally responsible manner. It is during this phase that the largest impacts can be mitigated most readily.

Metallurgical processes, such as froth flotation to concentrate pyrite and hence mitigate ARD, hydrothermal metallurgy for in situ oxidation of As^{+3} to the less toxic and more stable As^{+5} (Mambote, 2000), and bioleaching to catalyse the degradation of mineral sulphides such as pyrite or arsenopyrite (InfoMine, 2004), can have application in mineral recovery to produce a potentially less damaging waste product.

Potential pollutants can be separated out metallurgically for special disposal, such as within lined facilities leaving the bulk of the tailings in an inert state (Morro Velho, Appendix).

Reagent usage can be controlled to substantially reduce the environmental impact. The reagent type should be carefully considered to evaluate its potential environmental impact and the usage minimised through automated sampling and addition control.

A reagent that has the potential to be potentially harmful is cyanide used in the extraction of gold. For this reason many gold mining companies have considered detoxification and/or recovery systems as part of their metallurgical processes (Rule, 2001).

2.5.2 Dewatering technologies

It is said that future wars will be waged over water rather than oil (Meristö, 2003). Heavy industry, including metallurgical processing, requires pure water to run its processes. Dewatering of tailings prior to discharge to the environment is clearly important therefore.

Generally thickened tailings are produced using thickeners and paste using thickeners and filters. High rate and ultra-high rate thickeners were introduced over the last ten years or so to improve the efficiency of thickeners. Ultra high rate (paste) thickeners are used as an alternative to filtration, as this is costly and maintenance-intensive.

Thickened, paste and filter cake tailings materials are covered in the literature and is described in some detail in section 2.3.9 (Landform design).

2.5.3 Designing for geochemical issues

Covers

Two types of covers are used to isolate wastes and prevent ARD. These are referred to as dry and wet covers.

Dry covers

The dry cover approach aims to reduce the oxygen flux into the tailings, thereby minimising sulphide oxidation. The amount of acid water formed is also reduced by limiting the water percolation into the tailings.

A dry cover usually consists of a combination of drainage layers and sealing clay, inert or non-reactive tailings, geotextile and organic material. One such method is to cover the total impoundment area with polyethylene liner membrane. Dewatered and reagent-less tailings material is placed on top of the liner to act as an inert protective layer. A gravel and pebble layer or waste overburden is placed on top of the inert tailings.

The main drawback with the dry cover technique is that it is a relatively expensive approach that is difficult to get right.

Wet covers

Water covers are generally considered to be one of the most effective methods for the mitigation of potentially acid-generating tailings (MiMi, 2003). Underwater disposal below the hypolimnion in natural water bodies is preferred providing a deep water cover. The water cover in man-made lakes and in situ flooded basins is generally shallow (less than 2m) to minimise the size of dams constructed.

To limit metal transfer to the water cover protective layers of sand or organic material are sometimes placed over the tailings to act as a diffusion and mass-flow barrier.

A potential problem that should be mitigated is wind-induced mixing and re-suspension.

Liners

The use of liners, although common in municipal landfill and heap leach facilities, is significantly less common in tailings facilities outside of the United States of America (USA) (North American Examples A and B, Appendix).

Synthetic materials, such as high density polyethylene (HDPE) are often used with compacted clays to form a composite lining system to prevent polluted seepage through the facility foundation.

Liners are commonly used in the USA to facilitate the permitting process. This practice has however largely been avoided elsewhere on cost grounds. Increasingly however liners need to be considered as part of an encapsulation-type strategy (3.2.2 – Alternative strategies considered).

Under-drainage

Nowadays under-drains are commonly installed within impoundment walls to ensure stability. They are however increasingly being specified and installed to the basin area as well, at least beneath the planned operational limits of the supernatant pool. In this application, basal drains are installed above the liner, or foundations of suitably low permeability, with the intention of ensuring atmospheric pressure at the contact between the tailings material and the base, to limit seepage.

2.5.4 Co-disposal

Co-disposal of large volume mine wastes is sometimes practiced in an attempt to create a waste with altered, less potentially problematic characteristics. Wastes, typically tailings and waste rock or overburden, are discharged simultaneously at a single waste storage facility. The tailings particles fill the voids within the coarser waste material to produce a denser and therefore more efficient material. Deposition can be via combined pumping or by co-deposition. The problem with the former technique is rapid wear of the pumping system and the disadvantage with the latter is more complex depositional control.

The introduction of fines from the tailings material has the disadvantage that the geotechnical strength and permeability parameters of the coarser material are reduced.

The improved grading of the co-disposal material however offers the potentially substantial benefit of improved resistance to erosion, which is important for closure. Co-disposal covers are considered to offer the best potential for this technology (MMSD, 2002).

The deposition of tailings within a waste rock impoundment is also sometimes referred to as co-disposal (Figure 2.1.5).

2.5.5 Cold climate conditions

Special methods are adopted in extremely cold conditions. The issue of global warming however may mean that these techniques cannot be relied upon to provide a long-term solution for pollution prevention in the closure condition.

Layer freezing

The technique known as 'layer freezing' is used in permafrost zones to avoid the need to cap or line the facility with polyethylene membrane or similar. Tailings material is frozen upon deposition by careful management to ensure the freezing of layers of tailings to provide the required impermeability to prevent seepage from the tailings and precipitation.

The methodology that is used involves area preparation for tailings storage, tailings placement and containment prism building. The area is prepared by covering with heat-insulating material before the warm weather begins. Natural substances, such as moss, grass, peat and vegetation, are used to form this layer.

The next step is to remove this insulating layer prior to the onset of cold weather to ensure rapid freezing of the foundation. Tailings placement commences during the winter on the frozen base and takes place in layers of around 3 to 3,5m. Deposition continues in this manner during the summer but with a reduced layer thickness of less than 1,5m. Continuous monitoring ensures complete freezing of each layer. The main advantages of this technique are said to be implementation simplicity, reliability and low capital costs.

Final facility rehabilitation is undertaken by capping the tailings with gravel and pebbles or waste overburden material to form a stable final surface that is shaped at a gentle slope to allow water flow at a non-eroding velocity.

Frozen soil capping

For tailings facility closure in permafrost zones, frozen soil is used as a final capping layer and is protected from warming by covered with thermal insulating materials such as moss, peat, grass, timber processing wastes, *et cetera*.

Ice curtains

Ice curtains are sometimes used to act as a barrier to tailings water seepage through the subsoils from the impoundment to the environment. The curtain is formed along the axis of the facility impoundment using thermal siphons typically made of 200mm diameter steel pipes and using aviation kerosene. The thermal siphons are suspended in the boreholes that have been cased with 300mm diameter steel pipes. The gap between the siphons and the internal casing surface is filled with a sand/gravel mixture. The boreholes are typically sunk at 2,5m intervals along the impoundment crest and to a depth of 1,0m into bedrock.

Wet covers

Cold climates have several potential impacts on water-covered sulphide tailings. Factors that influence the effectiveness of a water cover include ice cover, snow cover on the ice and oxygen solubility in water (MiMi, 2003).

3. GUIDELINES FOR SUCCESS

3.1 Prelude

3.1.1 The need for guidelines

Closure of tailings storage facilities is particularly and perhaps uniquely difficult. The main reason for this is that facilities should be operated and maintained in a manner that assures their safety and physical and environmental integrity in perpetuity. Tailings facilities are very different structures to conventional water-retaining dams in that that the latter are typically designed to last a finite life and are designed, constructed and maintained to high standards. Tailings facilities, on the other hand, are usually constructed in stages or on a continuous basis over long periods, may be built by mine operators and often contain 'contaminated' materials.

Davies (2001) estimates that there are in the order of around 3.500 active tailings facilities world-wide. It is not known how many abandoned or closed facilities there are but the number is substantial and ever-increasing.

Since problems after closure can and should be viewed as another form of serious manifestation of facility failure, it is essential that solutions to this problem be identified and documented. Although much work has been undertaken in the past it is evident in the majority of cases, that closure techniques are mostly reinvented each time almost from scratch and that the lessons to be gained from failures and successes are not being translated into a useable and accessible form. An effective method of transferring learning in a succinct manner is considered to be via the production of guidelines that are updated as learning grows.

The guidelines contained within this volume aim to provide a summary of the most important factors and measures required to achieve lasting success. Although there are many guidelines and much technical literature published covering all aspects of tailings facility closure, this study endeavours to capture the key learning points and to distil the most important information into a practical and useful format for all those involved with the subject.

3.1.2 Issues to be addressed

The issue of how best to close tailings facilities should take cognisance of the idea of sustainable development if it is to succeed. The definition of sustainable development

should furthermore be interpreted in the context of improvements to quality of life and be associated with measurable indicators.

The work conducted for this study indicates the following potentially significant issues typically associated with tailings facilities.

- Groundwater quality and potential detriment from seepage caused by acid rock generation (ARD), heavy metal precipitation, high salinity, *et cetera*.
- Surface stability or erosion from wind and/or water.
- Air quality deterioration from dusting problems or emissions.
- Lack of adequate financial provision to address these issues in the longer term.
- Increasing social pressures for more land and a cleaner environment.

These issues should be successfully be addressed and mitigated for closure to be successful.

3.2 Strategies for Sustainable Closure

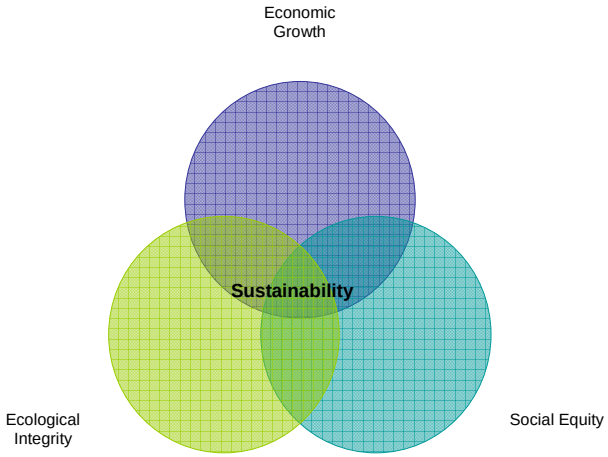
For the business of mining to be sustainable, the mining industry should successfully address the challenges associated with its activities in a way that '*meets the needs of the present without compromising the ability of future generations to meet their own needs*' (Brundtland, 1987).

The need for successful tailings facility closure is driven by:

- Legal and regulatory requirements.
- Company policy that conforms to sound corporate governance principles (King Commission, 2001 and Sarbanes-Oxley, 2002).
- Local development requirements to meet the expectations of the local community as typically defined in Environmental Impact Assessments and as part of the 'social license to operate'.
- Financial concerns to reduce long-term liabilities and costs and to increase stakeholder value through sound environmental management (Konar and Cohen, 2001).
- Sustainability as sustainable development principles should form part of company strategic planning and business decision-making.

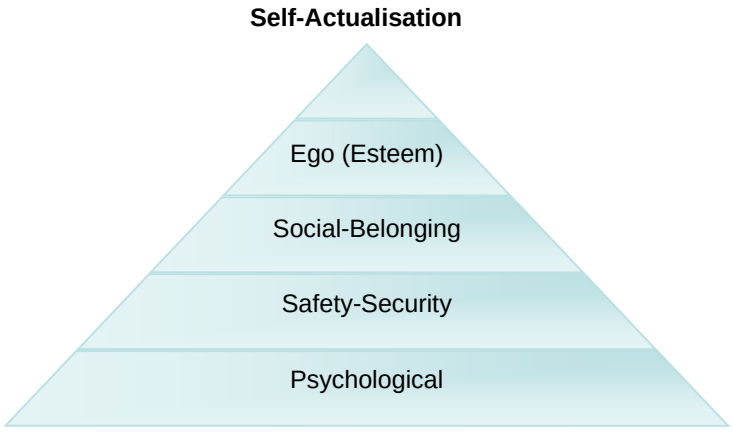
The mining industry requires a methodology for tailings facility closure to satisfy the aforementioned criteria. A new mindset is required.

Figure 3.2.1: Three Pillars of Sustainable Development



The closure process should take cognisance of the three pillars of sustainable development, namely economic, ecological and social dimensions (Figure 3.2.1) and should not adversely affect people's quality of life, as can be measured by consideration of the Hierarchy of Needs (Maslow, 1954) (Figure 3.2.2) at any stage in the future.

Figure 3.2.2: Maslow's Hierarchy of Needs



3.2.1 Background analysis

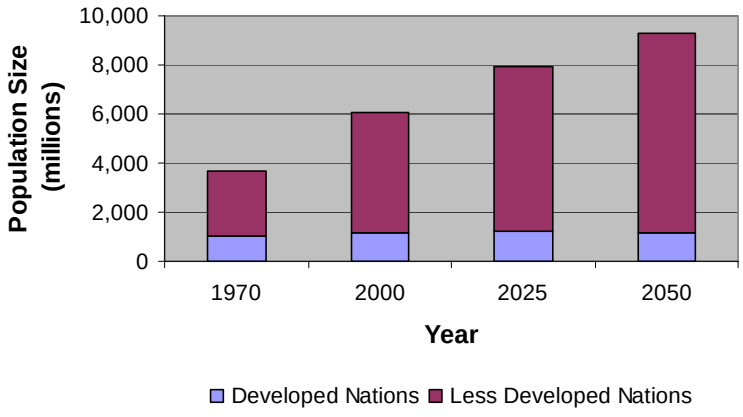
The future is notoriously difficult to predict and forecasts are often wrong. However, in determining closure requirements it is necessary to make certain assumptions about the future state of the world and the mining industry's place within it. The key factors that are

likely to influence the future are globalisation, people and social factors, political and economic factors, technology, and the physical and natural environments (Roux 2002).

The Earth Summit (1992) concluded that: '*The major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialised countries, which is a matter of grave concern, aggravating poverty and imbalances*'. This factor, when coupled with the rapidly expanding human population is a major obstacle to sustainable use of world resources and efforts towards sustainable development. To quote Brundtland (1994): '*It is simply impossible for the world as a whole to sustain Western levels of consumption for all. In fact, if 7 billion people were to consume as much energy and resources as we do in the West today we would need ten worlds, not one, to satisfy all our needs*'. Forecasts of world population growth (Figure 3.2.3) indicate that there will be over nine billion people in the world by the year 2050 (Roux, 2002).

Clearly therefore man should learn to do better and to conserve the scare resources provided by the planet's natural capital. Mining should play an important role in this regard as man can ill afford to continue the process of extracting mineral wealth to satisfy increasing consumer demand at the expense of the ecological and social elements of sustainable development.

Figure 3.2.3: Estimated global population size 1970-2050 (Roux, 2002)



Least likely case

Hawken (1999) presents the possibility of a Utopian-type world in which '*cities have become peaceful and serene because cars and buses are whisper quiet*', '*oil has fallen to $5 a barrel*', and '*living standards for all people have improved, particularly for the poor and those*

in developing countries'. Although this is a possibility if mankind appreciates that '*the limits to prosperity will be determined by natural capital, such as water, minerals, oil, trees, fish, soil et cetera*' and active and aggressive steps are taken to manage these resources responsibly, this model is considered unlikely. The main reasons for this are the population explosion that will continue until it becomes unsustainable, when wars, starvation, diseases or plagues associated with overpopulation restore the natural balance. The concept of 'externality' is likely to ensure that the human race fails to take the necessary steps in time for the common good at the expense of the individual.

Most likely case

The most likely case is considered below in the short-, medium- and long-term timeframes.

Short-term scenario

In the short-term or ten-year period, it is likely that mining companies would be made increasingly aware of environmental factors as a result of the 'shrinking world'. There would be cases of some companies becoming financially unviable as a result of requirements to account for the true costs of closure on their balance sheets and their inability to secure sureties for closure commitments. Many companies would try to evade their responsibilities as a result by selling those assets with high closure costs.

Medium-term scenario

In the medium-term or twenty-year period, it is likely that globalisation would result in greater uniformity of standards and regulations than before, with the influence of the two main world economies of the USA and European Union dominating. The effect on the mining industry would therefore be the adoption of relevant standards and practices deemed to be acceptable in either or both of these economies. This would be driven by demands from lending sources such as the World Bank as well as the influence of international pressure groups.

Mining companies would become more aware of the substantial benefits to be gained by sound environmental management as documented by Konar (2001), encouraged by the Global Reporting Initiative (2002) and the Kyoto Protocol (1997) with its system of credits that have value and could therefore be traded.

In the medium-term, the pressures placed upon the mining companies would result in higher standards, resulting in higher operating costs that should be passed on to the consumers.

Long-term scenario

In the long-term or fifty-year period, it is likely that the ever-increasing population size would result in greater demands on the natural resources and the environment. The influence of the main world economy of China would dominate. The demand for minerals would continue to grow despite the fact that many people in developed countries have much of what they require. The majority of the world's population however has a long way to go to match those in the developed countries. For the mining industry this would mean that lower grade ores would become viable resulting in more waste, or tailings material being produced. This waste would have to be safely stored in less space. These pressures, along with higher standards, would mean that mining companies would have to operate smarter using the available best technology and techniques.

Sustainable development practices would no longer be optional.

Uncertainties that characterise the scenarios

There are two critical uncertainties that could affect these scenarios, namely societal values and economic performance.

It is difficult to predict how societal values will change in the future. In the best case scenario, societies become more open, tolerant and giving with increased trust and industry and society embrace the principles of sustainable development. The other extreme is values could become more divided and rigid leading to conflict and distrust.

The fate of the world's economies will have a large role to play in characterising the eventual scenario. Industry could experience extended periods of strong commodity prices, growth and productivity improvement supporting the viability of new mines. On the other hand, there could be long periods of downturn. The economic viability of new mines and of closure activities, for that matter, would be limited.

3.2.2 Alternative solutions considered

In determining the best strategy for tailings facility closure it is necessary to identify and compare all available options.

Alternative options available for managing the issue

Four potential tailings facility closure methodologies exist. These in broad terms are:

- Symptom treatment.

- Encapsulate the tailings material or tailings facility to prevent pollutants from entering the environment.
- Render the tailings material inert prior to deposition.
- Find alternative uses for the tailings material to avoid disposal.

The possible solutions are influenced by the available site for tailings storage and factors such as proximity to the sea, open pits, exhausted underground workings, *et cetera*. For all options however, the goal of waste minimisation should apply. Mining of the ore body should be planned and conducted in a manner that will minimise the quantities of mining waste produced.

Base Case

This facility closure case represents the historical approach whereby science and technology were mostly applied to overcome and mitigate the results or symptoms of pollution rather than dealing with the problem at source. The majority of the cases studied herein (Appendix) are the result of this approach (Bibiani, Boddington, Córrego do Sítio, East Rand, Free State, Iduapriem, Jerritt Canyon, Morro Velho, Navachab, Obuasi, Sadiola Hill, Serra Grande, Siguiri, Tasmanian Example and West Wits). This approach is typically adopted as the capital and operating costs associated with tailings disposal are minimised. Mining projects are justified on this basis and financial models are not severely affected by the allowances made at the end of the project's life for the cost of closure. In addition, scientific and engineering experts have made good income from the work associated with the resultant on-going work.

With this approach the unacceptable environmental impacts of polluted seepage, low long-term physical stability, emissions to the atmosphere and undesirable aesthetics are treated as and when they materialise. More often than not mining companies that adopt this technique endeavour to undertake the minimum that is required by applicable legislation.

Problems that can be anticipated with this option include on-going liability in treating the symptoms, future liability issues as environmental standards are raised and recent initiatives such as the 'Polluter Pays Principle' that seeks to transfer the cost of dealing with pollution to those who caused the pollution. In some instances, unforeseen consequences can result as could occur in Peru where the mining company is legally obligated to provide water downstream 'in perpetuity' where downstream habitation and development occurs as a result of seepage from a tailings facility for instance.

Figure 3.2.4 (Base Case) depicts the potential methods of dealing with the problems that typically develop with this case.

Encapsulation Case

This closure case represents a higher level that the base case as efforts are made to prevent the release of pollutants to the environment thereby removing the need to treat many of the symptoms encountered with the base case. Some of the symptoms however remain as a result of the traditional tailings deposition techniques and technology adopted. Examples of this approach are Big Springs, Cerro Vanguardia, Coal Discards Dumps, ERGO Daggafontein, Geita, Morro Velho, North American Examples and Robinson (Appendix).

With this method the pollutants are trapped within the facility via one of two means; either by encapsulation of the tailings facility as a whole upon deposition or via fixing of the potential pollutants within the tailings particles themselves. The former is achieved by lining of the base of the facility prior to deposition to prevent seepage to the ground water table, and by covering of the upper surface and slopes of the facility after deposition has ceased. The latter could be achieved by chemical fixing of pollutants or by coating of the surfaces of the tailings particles with an impermeable and durable material prior to, or during deposition.

Potential pitfalls with this method are that liners are typically expensive adversely affecting the financial model and project profitability, and that even a small cost of chemical addition during operation accumulates to substantial sums with the high tailings tonnages produced. Other problems include the potential for long-term degradation of the liners, covers and chemical fixing or encapsulation agents causing future problems that would be costly to remedy at that stage.

Figure 3.2.5 (Encapsulation Case) depicts the potential methods of dealing with the problems that typically develop with this case.

Detoxification Case

This case is one in which potential pollutants are removed or treated prior to tailings deposition. This technique could result in the need for smaller ancillary disposal facilities to deal with separated contaminants. Examples of this approach are Mantos de Oro, Morro Velho, Sunrise Dam and Thickened Tailings Example (Appendix) although most of these projects have minimised water consumption and reagent usage rather than removal of other potential pollutants.

Typically the potential pollutants that would need to be dealt with are sulphides that could cause ARD, heavy metals, salinity, and reagents such as cyanide in the gold mining industry.

This area currently represents a growth industry as mining companies are realising the need to improve upon past environmental performance. Advantageous spin-offs are already being realised as mines gain from more efficient reagent usage, water-use minimisation and, in the gold processing industry, lower soluble gold losses.

In the treatment of sulphidic ores, the use of flotation could be considered to remove those particles that have elevated ARD potentials.

Figure 3.2.6 (Detoxification Case) depicts the potential methods of dealing with the problems that typically develop with this case. A good example of this approach is described in the Appendix (Thickened Tailings Example), not because the material has been detoxified, but because it was never toxic in the first place.

Alternative Case

This case represents a collection of options that could be considered for possible application. If such options are possible, they could possibly represent the best technique as they offer the potential for elegant and efficient tailings use that deals with other mining problems whilst removing or minimising the need for tailings facility closure. Examples that have adopted elements of this approach are Butchart Gardens, Eden Project, Paste Example, Tanami and Union Reefs (Appendix).

Tailings material could, in some instances, be returned underground and used to provide mine support for example. It is however never possible to return all such material underground however due to bulking upon mining and processing.

Provided that the tailings material is, or can be made inert, it could be used for mine rehabilitation efforts such as open-pit closure or as a soil substitute given amelioration and organic material addition.

It should be remembered that tailings material could potentially be a low-grade resource that could be economically exploited in the future. An example of this is provided by the East Rand Gold and Uranium (Appendix) operation that has made good business out of the re-treatment of old tailings facilities from central and eastern parts of Johannesburg over the

last twenty years. At this operation some tailings has been treated by a metallurgical plant up to three times to date.

Sale or use of tailings materials could also possibly be considered. As the earth's resources diminish the value of the tailings material could ultimately be realised.

Figure 3.2.7 (Alternative Case) depicts the potential methods of dealing with the problems that typically develop with this case.

Source of these options

The four options described in the preceding sections were obtained from a review of the numerous techniques that are being used to varying extents in different mines around the world. Figures 3.2.4 to 3.2.7 represent an attempt to categorise the techniques into potential closure strategies.

3.2.3 Two options selected for analysis and selection rationale

The Base and Detoxification case options were selected for the reason that the latter provides an inert tailings material that could be deposited in the majority of environments with the minimum potential long-term liabilities compared with the former, which represents the typical case. The Detoxification Case has been analysed for two sub-cases, namely 'surface' and 'sub-surface' deposition since tailings detoxification would permit environmentally responsible deposition on land or in disused pits, into lakes or into the oceans beyond the continental shelf.

The Alternative Case would obviously afford the ideal solution where the need for tailings closure would be minimised, but such solutions do not always exist and was therefore rejected for further examination.

The Encapsulation Case was rejected for the reason that it represents a half-way case between the Base and Detoxification cases and, as a result, fails to deal with all of the potential issues and could not necessarily be discharged to all receiving environments.

3.2.4 Comparative analysis of alternatives

Analytical comparison

The selected options have been compared using the 'multiple accounts analysis technique' (Robertson *et al*, 2001). The objective of the multiple accounts analysis is to assist with the identification of the most suitable or advantageous alternative by weighing the relative

benefits and costs or disadvantages of each. Three steps are involved, namely the identification of the impacts both positive and negative, quantification of the impacts, and assessment of the combined or accumulated impacts for each alternative.

The main benefits of this technique are that it provides a clear framework for evaluation that is defensible having given consideration to all potential issues and aspects. This analysis could be used to provide a forum in which stakeholders could express concerns.

Four categories of issues, or 'accounts', were defined in the analysis. These were technical, economical, ecological and social accounts, i.e. the three pillars of sustainable development plus the technical element. All potential stakeholder issues, called 'sub-accounts', were grouped under one of the main accounts and listed in the analysis. Sub-accounts were defined as any impact associated with any of the alternatives being evaluated. Within each sub-account, indicator values for that particular issue were defined to provide a clear, understandable description of the impacts.

The formal consideration of each of the different disciplines sheds light on the diverse problems of tailings facility closure that have not generally been given more than a cursory thought by engineers and planners in the past. The multiple accounts analysis technique assists with the decision-making process and ensures that issues from each discipline are given the appropriate weight.

Relative risks and benefits from the options

The risks posed by the cases considered are quite different. The Base Case represents the lowest technical risk as this has generally been the method widely adopted to date and much technical and scientific thought has gone into the 'treatment of the symptoms' commonly experienced. The Base Case however poses the greatest long-term risk as future liabilities are largely unknown and mining companies generally do not make financial provision for such liabilities in perpetuity. The result is therefore that the burden will have to be carried by future generations; clearly this is unsustainable.

The Detoxification Case (Surface) offers low long-term risks and therefore liabilities as the potential pollutants have been removed and cannot escape to the environment at any stage in the future. This applies to the Detoxification Case (Sub-surface) but this option has the added benefit that long-term structural degradation would not be a problem as could be experienced with the Detoxification Case (Surface).

Figure 3.2.4: Base Case

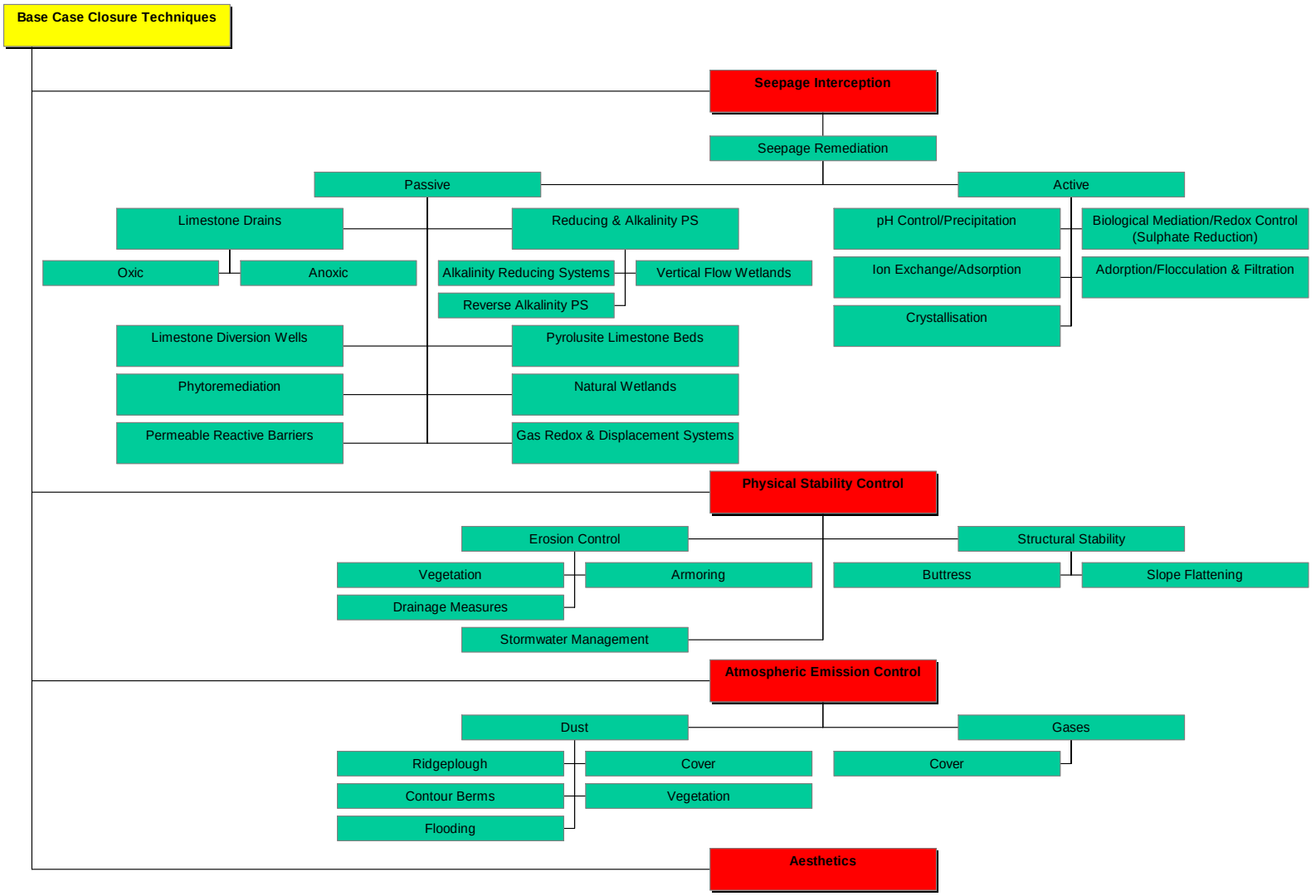


Figure 3.2.5: Encapsulation Case

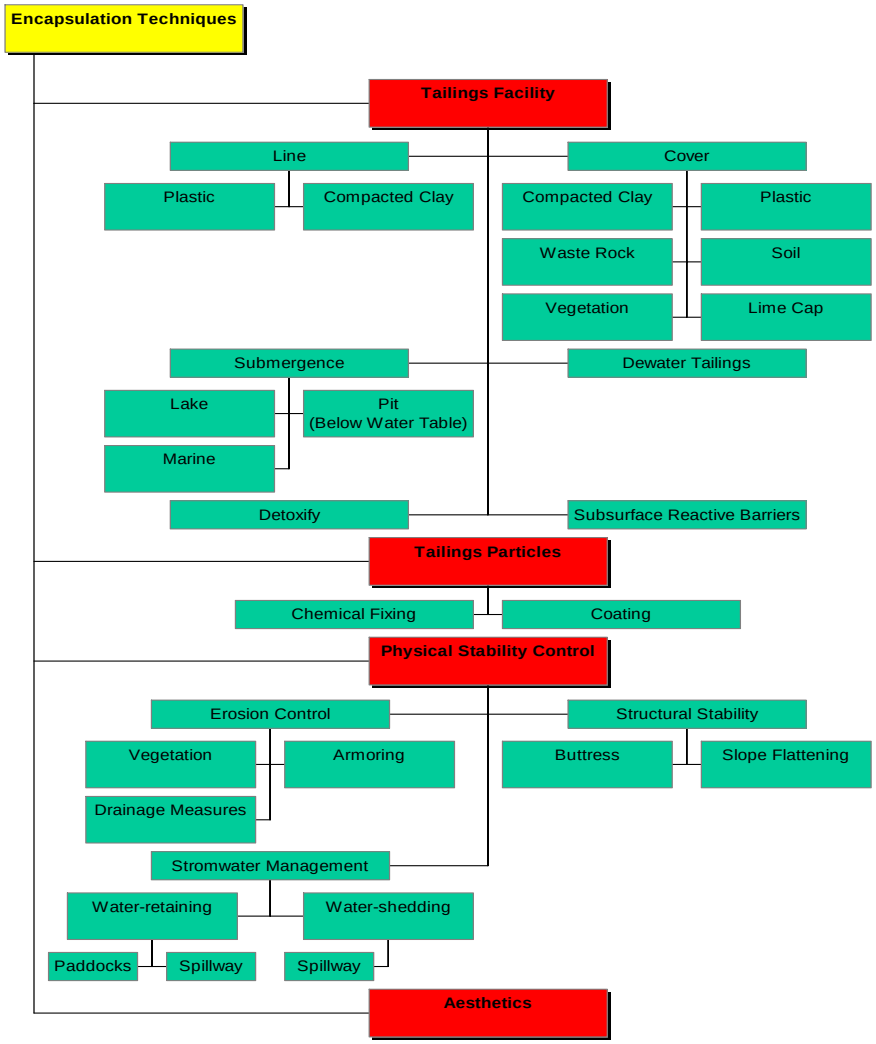


Figure 3.2.6: Detoxification Case

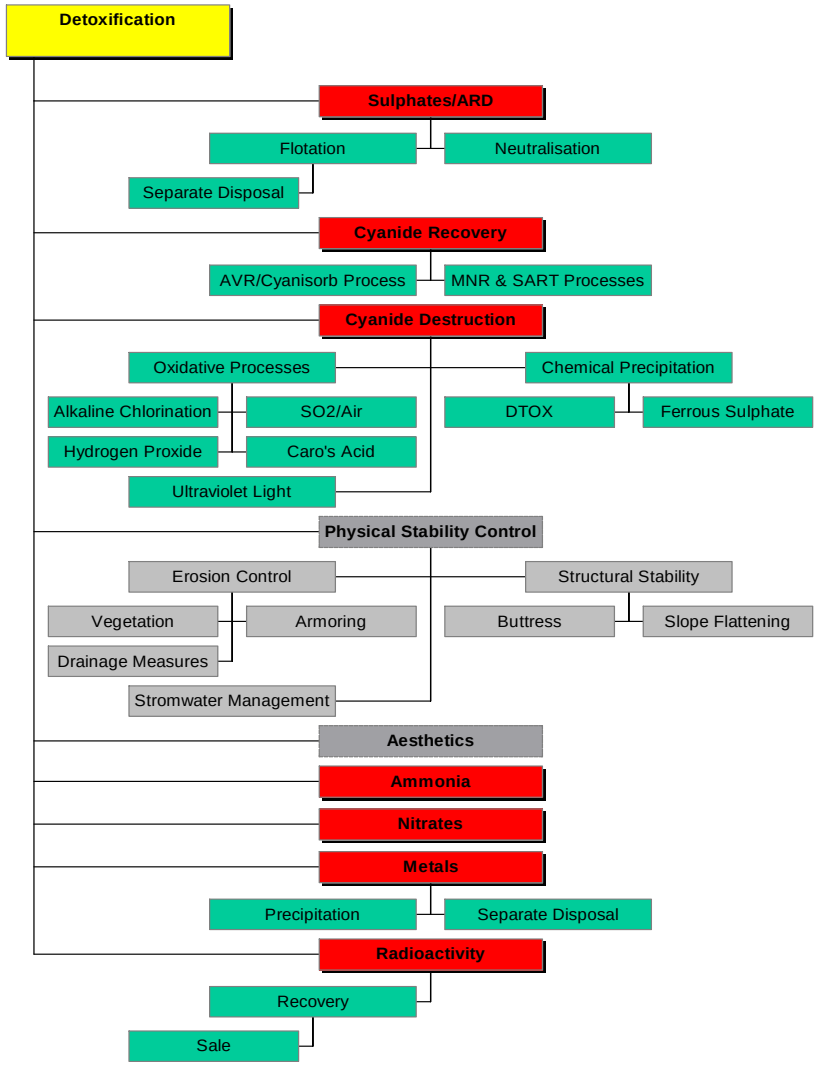
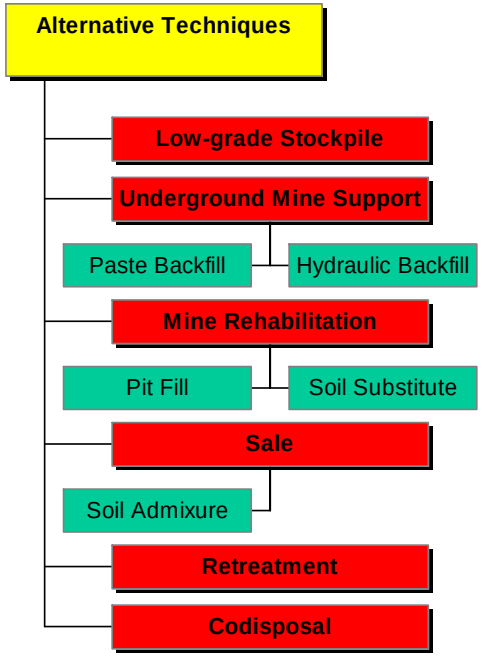


Figure 3.2.7: Alternative Case



The greatest risk associated with the Detoxification Case (Sub-surface)' is that of public opinion. Public perception that mining companies could be permitted to pollute the 'Great Common Green' (Hawken et al, 1999) of the oceans is likely to result in moves to ban this practice. As 'perception is reality' this would be a very difficult option to motivate despite its numerous benefits and the fact that all surface tailings facilities will ultimately be eroded and discharged in the sea by natural processes in geological time.

Conditions that alternatives could succeed

The Detoxification Case method could succeed at that point in time when the natural, political and social conditions are right. The natural conditions that would need to prevail are those where diversity remains and that such diversity is valued by a society that is willing to pay a premium for maintaining the natural capital.

The necessary political environment would be one in which regulators guide mining companies down the desired route of sustainable closure practices via a combination of incentives and ensure that all are working from the same base. The regulators however would have to be sure of the marginal cost of pollution to establish the incentives and penalties at realistic and effective levels.

Society would have to have developed to the level were it is possible for the objectives of sustainable development to be pursued globally rather than in limited locations as is generally the case today. So long as the tremendous disparity in wealth between nations and nationals remains, it is likely that differing standards will continue to be applied.

Conclusions from scenario analysis

The results of the multiple accounts analysis (Table 3.2.1) demonstrate that the best:

- Technical solution is provided by the Base Case.
- Economic solution is offered by the Detoxification Case (Sub-surface).
- Ecological solution by the Detoxification Case (Sub-surface).
- Social solution by the Detoxification Case (Sub-surface).

The Detoxification Case (Sub-surface) is the best overall solution, scoring 154 with the next best solution being the Detoxification Case (Surface) scoring 139. The worst solution is provided by the Base Case, which scored 102.

It can therefore be concluded that the method currently commonly used to effect tailings facility closure is the least desirable as it fails to provide the best overall solution, or for that matter, any of the three pillars of sustainable development.

3.2.5 Conclusions and findings

Since mine closure has evolved from being considered to be one chiefly of a scientific nature fifteen to twenty years ago, to being a socio-political and financial problem today, it is necessary to ensure that sustainable development principles are adopted. Should this not be achieved mining is unlikely to be a sustainable business. Mining companies that ignore social equity or ecological integrity in pursuit of economic growth, the traditional focus, do so at their peril. Such organisations will quickly discover that their 'social license to operate' is removed should the mining activities interfere with people's needs and expectations.

How to solve the problem and attain goals

Designing tailings facilities with the end in mind right from the start could solve the problem of achieving sustainable tailings facility closure. The traditional approach of designing a facility to suit whatever material the metallurgical plant happens to produce should not be accepted. The mining process should, wherever possible or necessary, be modified to produce a tailings material that could safely be disposed of and be expected not to provide any deleterious affects to the receiving environment even in the long term.

Recommended course of action

It is recommended that mining companies give serious consideration to embarking upon tailings facility closure properly. In essence this could be achieved by adopting the Detoxification Case as a company model for tailings facility closure in place of the currently adopted Base Case model. Although this would require a paradigm shift in corporate-thinking, it is likely that an increasing number of mining companies will be directed in this direction by social and legislative pressures that will impact upon the economic sphere of the mining companies, which is when the shift is likely to occur.

Table 3.2.1: Multiple accounts analysis of Base & Detoxification case models for tailings facility closure

ACCOUNTS	ISSUE	INDICATORS	WEIGHT	BASE CASE	DETOXIFICATION CASE	
					SURFACE	SUB-SURFACE
TECHNICAL	Seepage interception	Trenches	3	3	5	5
		Drains	3	3	5	5
		Wells	3	1	5	5
		Impermeable membranes	3	5	5	5
		Grout curtain	3	5	5	5
		Sub-account Score:		3.40	5.00	5.00
	Seepage remediation	Limestone drains	3	3	5	5
		Reducing & alkalinity passive system	3	3	5	5
		Limestone diversion wells	3	3	5	5
		Phytoremediation	3	3	5	5
		Permeable reactive barriers	3	3	5	5
		Pyrolusite limestone beds	3	3	5	5
		Natural wetlands	3	4	5	5
		Gas redox & displacement systems	3	3	5	5
		pH control/precipitation	3	2	5	5
		Ion exchange/adsorption	3	2	5	5
		Crystallisation	3	2	5	5
		Biological mediation/redox control	3	4	5	5
		Adsorption/flocculation & filtration	3	2	5	5
		Sub-account Score:		2.85	5.00	5.00
	Structural stability	Erosion control	3	1	1	5
		Structural stability	3	3	3	5
		Buttress	3	3	3	5
		Slope flattening	3	4	4	5
		Vegetation	3	3	3	5
		Armouring	3	3	3	5
		Drainage measures	3	1	1	5
		Storm water management	3	2	2	5
		Sub-account Score:		2.50	2.50	5.00

	Atmospheric control	Dust generation	3	3	3	5
		Ridge-ploughing	3	1	1	5
		Contour berms	3	1	1	5
		Flooding	3	1	5	9
		Cover	3	4	4	5
		Vegetation	3	3	3	5
		Gas emission	3	3	5	5
		Sub-account Score:		2.29	3.14	5.57
	Acid rock drainage	Flotation	3	5	2	2
		Neutralisation	3	5	2	2
		Separate disposal	3	5	4	4
		Sub-account Score:		5.00	2.67	2.67
	Ammonia	Ammonia detoxification	3	5	2	2
		Sub-account Score:		5.00	2.00	2.00
	Nitrates	Nitrate treatment	3	5	2	2
		Sub-account Score:		5.00	2.00	2.00
	Metals	Precipitation	3	5	2	2
		Separate disposal	3	5	4	4
		Sub-account Score:		5.00	3.00	3.00
	Radioactivity	Recovery	3	5	9	1
		Sale	3	3	9	1
		Sub-account Score:		4.00	9.00	1.00
	Cyanide recovery	AVR/Cyanisorb process	3	5	2	2
		MNR & SART processes	3	5	2	2
		Sub-account Score:		5.00	2.00	2.00
	Cyanide destruction	Alkaline chlorination	3	5	2	2
		Hydrogen peroxide	3	5	2	2
		Sulphur dioxide/air	3	5	2	2
		Caro's acid	3	5	2	2
		Ultraviolet light	3	5	2	2
		DTOX	3	5	2	2
		Ferrous sulphate	3	5	2	2

		Sub-account Score:		5.00	2.00	2.00
	Account Score:			**45.03**	**38.31**	**35.24**
ECONOMIC	Capital costs	Civil engineering costs	5	9	1	3
		Mechanical plant costs	5	9	1	1
		Design & supervision costs	5	9	7	5
		Material costs	5	5	3	4
		Energy costs	5	5	5	7
		Water costs	5	5	5	5
		Labour costs	5	1	3	5
		Sub-account Score:		6.14	3.57	4.29
	Operational costs	Cost of environmental surety/bonds	5	1	9	7
		Cost of insurance	5	1	9	7
		Reagent costs	5	8	1	1
		Water costs	5	3	7	7
		Power costs	5	5	6	8
		Labour costs	5	5	4	8
		Sub-account Score:		3.83	6.00	6.33
	Closure costs	Cost of closure	5	1	7	9
		Water costs	5	5	5	9
		Power costs	5	5	5	9
		Labour costs	5	3	3	5
		Sub-account Score:		3.50	5.00	8.00
	After-care costs	Labour costs	5	5	3	9
		Power costs	5	5	3	9
		Reagent costs	5	8	1	1
		Professional input costs	5	5	5	9
		Sub-account Score:		5.75	3.00	7.00
	Project profitability	Short-term profitability	5	9	1	2
		Long-term profitability	5	1	6	9
		Potential for future comebacks	5	1	5	2
		Sub-account Score:		3.73	3.00	4.13
	Account Score:			**22.96**	**20.57**	**29.75**

ECOLOGICAL	Surface water quality protection	Degree of protection	5	1	7	9
		Sub-account Score:		1.00	7.00	9.00
	Surface water quantity protection	Degree of protection	5	1	7	9
		Sub-account Score:		1.00	7.00	9.00
	Groundwater quality protection	Degree of protection	5	1	7	9
		Sub-account Score:		1.00	7.00	9.00
	Biological & vegetative potential	Density of re-vegetated areas	3	5	1	9
		Ecosystem diversity/sustainability	5	2	7	5
		Compatibility with wildlife habitat	4	3	7	1
		Sub-account Score:		3.70	4.40	3.73
	Account Score:			**6.70**	**25.40**	**30.73**
SOCIAL	Aesthetics	Blend with natural landforms	4	5	5	9
		Amelioration of other elements	3	1	5	9
		Sub-account Score:		3.29	5.00	9.00
	Future burden on society	Sustainable development	5	1	8	8
		Sub-account Score:		1.00	8.00	8.00
	Recreation	Potential for beneficial use	3	5	7	9
		Sub-account Score:		5.00	7.00	9.00
	Agriculture	Potential for agriculture	3	3	7	9
		Sub-account Score:		3.00	7.00	9.00
	Employment opportunities	Construction	3	5	3	9
		Operation	3	8	1	1
		Closure	3	1	7	9
		Post-closure	3	1	7	9
		Sub-account Score:		3.75	4.50	7.00
	Health risk to population	Drinking water	5	2	8	9
		Risk of structural failure	5	2	2	9
		Atmospheric pollution	5	1	9	9
		Food chain	5	1	9	9
		Radiation	5	3	9	9
		Sub-account Score:		2.25	9.25	11.25
	Public perception	Perceptions	5	5	9	1

		Stakeholder acceptance	5	4	9	1
		Sub-account Score:		4.50	9.00	1.00
	Company image	Shine	4	5	9	1
		Market capitilisation	5	5	9	2
		Competitive advantage	4	5	3	7
		Sub-account Score:		4.33	4.43	4.20
	Account Score:			**27.12**	**54.18**	**58.45**
MULTIPLE ACCOUNT SCORE:				**101.81**	**138.46**	**154.17**

	Scalar Values:
9	Best
8	Very Good
7	Good
6	Slightly good
5	Intermediate
4	Slightly poor
3	Poor
2	Very poor
1	Worst

Weight Factors:	
5	Most important
4	
3	
2	
1	Least important

Sub-Account Score=(Sum of Scalar Values x Weights)/(Sum of Weights)

Reasons for recommended course of action

The main reasons for the recommended course of action is that if the problem of tailings facility closure is handled in the stated manner, one of the biggest closure liabilities would be handled properly and in a potentially sustainable manner. The advantages to the mining companies would be numerous:

- Limiting the cost of facility closure.
- Minimising the long-term liabilities.
- Reducing exposure to future changes in environmental legislation.
- Reducing the financial securities that would be required when mining commences as the custodians of social equity and ecological integrity would be assured of lower levels of risk.
- Enhancing company and industry image thereby maintaining the social license to operate.
- Enhancing stakeholder value through market recognition of improved environmental performance and commitment to sustainable development.
- Accessing environmental credits that could be traded or used if necessary.
- Obtaining a competitive edge.
- Facilitating the permitting process, as company image and track record will count with the regulators.
- Reducing future comebacks or surprises.
- Obtaining closure certificate and the associated termination of many obligations.

Recommended process for implementation

The following process is recommended for implementation:

- Develop implementation strategy.
- Use Strategic Environmental Assessment (SEA) to redefine company policy.
- Start the process immediately.
- Make the necessary resources available.
- Allocate responsibilities and accountability.
- Obtain the involvement of the government and community.
- Manage expectations.
- Define community and employee needs.
- Employee and community training for the post-closure situation.
- Obtain closure certificate.
- Publicise success.

Potential pitfalls

The best way to deal with the unknown is to identify potential pitfalls so that their effect can be considered and mitigated where possible.

The possible pitfalls are:

- Moving goalposts in terms of social expectations and legislative requirements. The recommended option however minimises the potential for problems.
- Unforeseen and unpredicted social and economic problems.
- The recommended strategy is capital and operating cost-intensive, which could adversely affect the economic viability of the project resulting in lack of development. Traditional accounting techniques do not favour capital and operating cost-intensive methods (Ruse, 2003). The Base Case model defers closure costs to the end of the project where they affect the project NPV the least.
- Higher costs should ultimately be passed on to consumers, which is possible during periods of growth but could become untenable during periods of economic decline.

3.3 Key Criteria for Successful Closure

It is essential that the criteria for successful closure are established. Once this has been done it should be possible to develop procedures and techniques to provide a means by which success can be demonstrated and predictions made about likely post-closure performance.

Closure criteria are required to:

- Indicate whether closure has been successful.
- Assist with the design of monitoring and rehabilitation programmes.
- Enable the mining company to relinquish the mining lease without incurring further liabilities.
- Confirm that that the post-mining land-use is likely to be sustainable.
- Enable adequate financial provision to be made for closure liabilities.

Closure criteria have a significant impact on the scope and cost of mine closure programs. Producing closure criteria that will satisfy the technical scrutiny of regulators and stakeholders and yet be appropriate and achievable for each particular mine and locality represents one of the most challenging aspects of closure planning.

Closure criteria relate to post-mining landscape condition and proposed land use, soil quality and water (surface and groundwater) quality, vegetation and faunal habitat status, aesthetics and access.

Although criteria for sustainable closure should be site-specific, carefully considered and properly defined for each tailings facility, key criteria for tailings facilities would however typically include most, if not all, of the following:

3.3.1 Baseline data

Baseline data are an essential component of any closure criteria and should include geochemical, hydrological and hydro-geological information.

Geochemistry

Geochemical characterisation should be undertaken to achieve an understanding of the geochemistry of tailings material and tailings pond water. This data should ideally have been gathered and recorded at regular intervals throughout the operational life of the facility to ensure that any changes in the ore and/or metallurgical processes are evident and recorded. The collected data should also be of such a nature that potential changes in the chemistry of the tailings material through oxidation and weathering are detected.

Climate, hydrology and hydro-geology

Site-specific climatic data should be recorded throughout the operational life of the mining operation and during the after-care period. Long-term historical records should, where possible, be obtained for the region.

Baseline hydrological studies of the tailings facility site and surrounding area should be conducted and long-term records kept of the climatic conditions of the tailings facility site and the surrounding area.

Baseline hydro-geological studies should be conducted and long-term records kept of the climatic conditions of the tailings facility site and the surrounding area.

Surface water and groundwater quality assessments are essential, including establishment of field sampling stations, QA/QC protocols controlling collection and analysis of samples, and evaluation of water quality and water level data.

Hydrological processes should be modelled using information derived from field investigations to provide the basis for computer analyses that predict the impacts of changes or development on catchment flows, groundwater recharge and discharge characteristics, surface and subsurface solute movement, and water quality and groundwater flow patterns. This approach is especially important in designing strategies for decommissioning and rehabilitating mine sites, especially when one of the key drivers is to engineer, as closely as possible, the pre-mining surface water and groundwater flows and conditions.

Social issues

Social issues are becoming increasingly important and are beginning to influence closure activities more profoundly than before. Baseline data on human habitation should therefore be obtained and recorded to ensure that potential needs can be identified and predicted.

3.3.2 Responsibility definition

The typical hierarchy of responsibility for remediation can be summarised in most instances as being, in the first instance 'polluter pays' (current mining company initially followed by previous operators where they can be traced). Next in line is the owner (followed by previous owners), the lender (mortgage in possession), and in the last instance the state. Responsibilities may be transferred but approval is usually required from the regulatory authorities before this can be done. Essentially however the polluter remains liable in perpetuity.

Responsibility for closure and each of the various elements or stages of the process should be stipulated and documented.

3.3.3 Stakeholder requirements

Stakeholder requirements, including those of the regulators and neighbours, should be specified in the closure criteria. The requirements should have been obtained by public and community consultation processes, close communication with legislators amongst other methods.

Society and its impression of mining activities have a large influence upon many aspects of the way in which the mining industry conducts its activities. Mining is perceived to be an unnecessary, harmful, damaging and unsustainable practice that exploits indigenous populations. If society is to continue to tolerate mining, the mining industry needs to modify or change the techniques used. For example, many in society consider the use of cyanide,

heap leach and open-pit mining techniques and conventional tailings facilities unacceptable. The mining industry must find better ways of mining, processing and waste disposal for society to accept our practices to be able to demonstrate that 'the place was better off for having been there' (Godsell, 2004).

3.3.4 Definition of long-term objectives

The closure criteria developed for the facility should include definition of the long-term objectives with description of the end use for the rehabilitated site. Unless this key objective has been defined at the start, the closure project is destined to fail.

3.3.5 Design criteria

Given the long-term exposure after closure, definition of appropriate closure design criteria should include designing for the probable maximum flood (PMF) and the maximum credible earthquake (MCE).

Allowance for limited historical data sets should be made and also for the uncertainty around global warming issue and the potential impact upon climatic extremes.

3.3.6 Ecosystem processes

Ecosystem processes should receive full consideration with a key objective being to build a 'living system' that has the capacity to thrive in the long-term. Ecosystem processes that are important in ensuring the sustainability of a site are soil stability, water infiltration, nutrient cycling, vegetation and fauna.

Soil or growth media stability

Soils are fundamentally important to rehabilitation success. The main functions that soils undertake are to provide a medium for plant growth and a nutrient and water store. They are essential for nutrient cycling and are central to landscape evolution.

Soil stability is achieved via a long-term process with turnover of litter and soil organic functions taking place over tens of years in the uppermost horizon, and thousands of years with depth.

The soil properties that relate to soil function are (Hinz, 2004):

- Physical properties such as soil water storage, e.g. field capacity, hydraulic properties (water flow) and structural stability determined by bulk density, texture and porosity.

- Chemical properties such as pH and nutrient contents affected by cation exchange capacity, exchangeable sodium and electrical conductivity.
- Biological properties such as microbial respiration and root distribution.

Tailings characteristics

Although tailings material can be directly vegetated under some conditions, tailings material alone is a poor growth media due to a lack of structure, poor moisture retention characteristics and a lack of fertility and micro biota. When cover material is used and unless the tailings material is highly acidic, plant roots will propagate into the tailings and reduce deep percolation, effectively acting as an evapo-transpirative cover. Limited oxygen ingress occurs into the finer grained tailings and long-term acid generation may be limited to the near surface (Milczarek, 2004).

Tailings can generally be classified into three textural types corresponding to the location within the facility. Coarse- to fine-grained sands occur at and close to the deposition points. Sandy silts occur in the perimeter mixed zones. Silt occurs in the decant area. The latter two types comprise the bulk of the tailings material. Silts and sandy silts have high moisture retention but low permeability, which can reduce infiltration and impede root penetration. Although the addition of organic matter to the tailings improves the textural properties and fertility, the long-term effects may be limited. Moreover for sandy tailings, often used for perimeter wall-building purposes close to the deposition points, limited water availability and high erosion rates make vegetation establishment virtually impossible (Milczarek, 2004).

Figure 3.3.1: Poor vegetation growth in tailings material



The addition of nominal thicknesses (less than 300mm) of growth media significantly affects the revegetation of non-acid tailings. Primary roots growth occurs in the growth media but rooting extends at depth into the tailings to extract moisture during dry periods. High moisture retention in the sandy silts and silts can result in short-lived vigorous growth of deep-rooted tress and shrubs soon after rehabilitation. Even with thick covers where the roots do not extend into the tailings, the moisture retained in the tailings can be wicked via evapo-transpiration demand during dry periods (Milczarek, 2004).

The implications of tailings characteristics for rehabilitation design are (Milczarek, 2004):

- Non-acid forming tailings material can be vegetated with nominal cover thickness and/or amendments.
- Vegetated tailings/cover systems can serve as highly effective evapo-transpirative covers.
- Acid-forming tailings material can be covered but wicking of tailings solution into the cover may occur.
- Long-term tailings drainage can take decades or longer to cease.

Water infiltration and seepage

Achieving the correct soil water balance is the initial step in managing rehabilitation efforts.

Infiltration rates are dependent upon the soil properties. For example, non-cohesive sodic soils high in clay content have low infiltration rates due to surface sealing and pore clogging resulting in hard-setting limiting root growth, crusts limiting seeding emergence and run-off causing erosion. On the other hand, non-cohesive sandy materials have high infiltration rates with sub-surface runoff causing tunnelling and gulley formation.

Clearly therefore one should take cognisance of the soil types available for use in rehabilitation efforts as they will profoundly influence the amount of water available for vegetation growth, the amount of seepage generated from the facility and the amount of surface run-off that would affect erosion.

The high moisture-retention characteristics of many tailings materials can mean that tailings drainage, and hence seepage, will continue for centuries, depending upon the size and construction methods of the tailings facility.

Nutrient cycling

Nutrients in a sustainable eco-system cycle through soil organisms, plants and fauna. In terrestrial eco-systems most nutrient cycling takes place in the upper-most horizons in the soil. The main inputs to the soil come from weathering, rainfall, fertilizers, atmospheric sources and organisms. Under natural conditions, inputs from plants are the most important, including not only nutrients released by organic decomposition, but also substances washed in from the plant leaves (foliar leaching). Losses or outputs occur by leaching, erosion, gaseous loss, such as de-nitrification, and plant uptake. Within the soil, nutrients are stored on the soil particles, dead organic matter, or in chemical compounds (PhysicalGeography, 2004).

Organic matter is essential to soil health since organic matter decomposition is the main process that recycles nutrients back into the soil. Decomposition of organic matter begins with large soil organisms such as earthworms, arthropods and gastropods, which break the organic matter down into smaller pieces that can be decomposed by smaller organisms such as fungi and heterotrophic bacteria (PhysicalGeography, 2004).

Benefits of a humus-rich soil include (Beetz, 2002):

- Granulation of soil particles into water-stable aggregates.
- Decreased crusting.
- Improved internal drainage.
- Better water infiltration.
- Fixation of atmospheric nitrogen.
- Release of bound nutrients.
- Increased water and nutrient storage capacity.

The use of pasture plants to cycle nutrients should be considered. Rhizobium bacteria live in legume roots nodules and convert nitrogen from the air into forms that the legume can use. This nitrogen is used by the plant and generally does not become available to adjacent plants until the legume dies. Some of the nitrogen fixed by white clover however is available as soon as four months into the season. Red clover takes six months and alfalfa-fixed nitrogen takes six to twelve months to become available (Beetz, 2002).

Another way in which nutrients are released to the cover plants is through the action of deeply rooted plants. Trees, many broadleaf weeds and forages such as alfalfa have taproots that go deep into the soil horizon where grass roots cannot reach. The nutrients from these deeper horizons are used by the plant but become available at the soil surface once the tree leaves fall or the weeds die releasing their nutrients (Beetz, 2002).

Although supplementing the nutrient cycle with commercial fertilizers, compost or manure increase both plant and fauna production, sole reliance on them short-circuits the natural mineral cycle. High fertilization coupled with frequent harvesting of hay speeds organic matter decomposition and releases mineral faster than the plants can absorb them. As a result, nutrients are leached deeper into the soil or are lost to run-off (Beetz, 2002). It is preferable to find ways to use natural systems wherever possible if a sustainable outcome is to be achieved.

Lime addition should be considered as application (Nation, 1995):

- Prevents weeds.
- Assists with the movement and absorption of phosphorus, nitrogen and magnesium.
- Benefits bacteria, fungi, protozoa and other soil life essential for nutrient cycling.
- Releases important trace and growth nutrients via the pH-altering affect.
- Helps clover growth, which requires twice the calcium of grass and is necessary for clover nodulation.
- Creates soil tilth and structure so that air and water can move freely through the soil causing clay particles to adhere to each other.
- Increases drought resistance.
- Improves the palatability of grass and clover, makes the pasture softer for animals to graze and lessens the grass-pulling in new stands.

Two practical indicators of soil health are the number of earthworms and the percentage of organic matter in the soil (Beetz, 2002).

Vegetation

The vegetation that is to provide long-term stability after rehabilitation should be as resilient as the ambient vegetation.

The best approach to vegetation establishment is one based on research with the implementation of methods tailored for the different conditions found at mine sites (for example, strip mines such as bauxite and mineral sand operations compared with hard-rock operations where gold, base metals and uranium are mined).

Particularly important are the availability and management of seed and other propagating materials, site preparation and vegetation establishment techniques, fertiliser strategies, weed and fire management, predictability of revegetation performance, and monitoring criteria and methods.

Weed identification, weed mapping and control methods for controlling or eradicating weed populations should not be overlooked.

The long-term effects of salinity from the tailings solution and capillary-action on vegetation should be studied and understood.

Fauna

The potential issue of exotic and feral animals should be assessed and managed.

Desirable species should be encouraged via, for example the provision of perching opportunities for predatory birds to control the rodent population, or the planting of vegetation that attracts insects which in turn attract bird life.

3.3.7 Financial requirements

A climate that encourages closure activities should be encouraged. Tax-rebates or incentives could be used to create work or stimulate sustainable development.

3.3.8 Sustained growth

Suitable vegetation should exhibit sustained growth and development and not require re-seeding or re-planting. The seeds produced by the vegetation should not be sterile and should be capable of germination.

Vegetation should not require artificial irrigation or fertilization in the long-term once established.

Vegetation should be compatible with that found naturally in the areas adjacent to the facility, or on the analogue or reference sites, and should not be invasive or otherwise capable of upsetting the indigenous habitat.

3.3.9 Landform design

Landform design is an area that has generally been ignored during tailings facility closure until recently. This is a fundamental mistake and should therefore be addressed by designers (Jones, 2004).

Engineered structures

Engineers have developed ways in which to ensure that the structures they design are durable in the short and medium-terms. In engineering terms most man-made structures are considered to be acceptable if they survive for between fifty and one hundred years before significant maintenance or demolishing is required. This is true for water-retaining dams, which are relatives of tailings facilities in a sense. Large water dams however are usually carefully engineered using the most durable construction materials such as concrete, are built using strict quality control standards, and are properly maintained during their

operational lives. Despite this, water dams often show signs of significant deterioration within a hundred years. Tailings facilities should remain stable for far longer periods, some would argue in perpetuity. For this to be possible, closure designers should observe and learn from natural landform evolution processes.

The key fact that cannot be ignored in landform design is that the landform will evolve. The challenge is how to design to avoid retro-active work or rectification. The way to do this is to design the facility or landform to work in empathy with nature.

Weathering and mining

Most deep open pits show the sequence of weathering clearly with soils the result of long-term weathering of *in situ* rocks or transportation at or near the surface. Beneath the soil horizon are the weathered, oxidised rocks, which are typically relatively inert and low in potential pollutants with characteristics that facilitate relatively simple metallurgical extractive processes. The deepest materials are partially or un-weathered rocks often containing sulphides and other potential pollutants.

Even resilient rocks such as granite and basalt break down in time with primary minerals decomposing to secondary minerals. All minerals, with the exception of quartz, decompose to clays. Rock extracted from depth underground experiences pressure-relief and is exposed to atmosphere. Mining activities initiate natural decomposition processes in this manner.

Learning from nature

Current mine residue disposal practices often result in flat-topped structures with perimeter slopes. If tailings facility designers want to create durable flat-topped structures they should emulate nature. The Australian landform provides excellent lesson as the surface is ancient and has attained a stable state with virtually no erosion or accretion: the hills that exist are flat-topped structures capped by harder material.

Designers should take extreme rainfall and flood events into account as these are what cause the most damage in terms of water erosion. Even the most arid climatic zones show evidence of tremendous surface water flows at times. It is a common design fault to consider relatively short-term data (one hundred years at best in many instances) and not to make adequate provision for storms, despite evidence of past large floods that could conceivably reoccur or be exceeded during the post-closure condition.

A golden rule associated with storm water management design is that water will always find a short cut.

Wind is a substantial force that causes significant erosion despite the presence of vegetation. There is much published data on the rapid erosion of tailings facility slopes despite grasses used for stabilisation (Blight, 2003).

The influence of earth's gravity means that there will be movement if there are interfaces within soils.

The extent and rate of slope erosion depends on the length of slope, angle of slope and cohesion of material of slope. Tailings facilities have often been designed and constructed with slopes that fall within the range of slope angles that are the most susceptible to erosion. Flatter or even steeper slopes would be less susceptible (COMSA, 1979a). Flatter slopes have not been universally adopted for tailings facilities to economise on the required footprint and to minimise the associated capital cost. Steeper slopes are more problematic geotechnically although there are examples of exceptionally steep slopes where rise rates have been very low.

Closure designers should understand the material that will be used in the landform (section 3.3.6 Ecosystem processes). Topsoil for example does not necessarily have the correct properties to remain on the slopes when removed from the plains. The tailings and capping soil mineralogy should be examined by undertaking practical tests to establish the factors that could assist as evolution takes place.

The key lesson is that one should observe and learn from nature and duplicate natural solutions (Jones, 2004).

Geometrical design

An understanding of the materials coupled with an appreciation of the natural forces acting on the facility should result in the design of the slopes found in natural, ancient landforms and not young slopes prone to erosion (Jones, 2004).

Engineers commonly make use of benches and berms to shorten slope lengths and control water flow in this way. This approach, although effective in the short-term where properly engineered, is not a long-term solution as berms will trigger the development of gulleys in most circumstances. A related technique known as scalloping has been tried and found to

be remarkably successful in some instances but depends upon the material. It should however be remembered that all materials weather, but the rate of weathering varies. Berms are concentrators of water flow, which is acceptable provided integrity is not breached. Designers should however remember that there are no horizontal structures on natural slopes and that nature will therefore remove the berms in time.

Steeper slopes with berms are not considered an acceptable way of accelerating the landform to stable, advanced stage as they are not durable. As there is a real cost of flattening slopes the aim should be to construct the facility at the correct angle from the start wherever possible.

Flat-topped facilities are not landforms that will survive.

Alternative approaches

Alternative approaches can be extremely expensive at the onset. Owners and operators therefore need to adopt a new mindset to create a sustainable landform as early as possible to try to advance from a 15-year to a 1.000-year geometry.

New mindset

One example of a 'new mindset' approach is to integrate mine planning with that of residue disposal making use of rigorous design tools that been developed over the past twenty years for open pit design (Jasper, 2004). This methodology is contrasted to that of waste landform design which is often cursory with empirical designs resulting in a compromised environment. Since the bulk of the mining equipment fleet can spend up to half its operating life on waste landform it is important to properly plan their activities to achieve more cost-effective designs that construct landforms that will meet closure requirements during the operations than to superimpose these once mining has been complete. This should include the management of inhospitable materials at the earliest stages to reduce risk of exposure and an on-going liability (Biggs, 2003).

The use of pit waste material to contain the tailings is not a new practice, but is one that is often overlooked. Some examples of the use of waste rock to produce integrated landforms include the Chalice, Telfer and Bronzewing mine in Australia (Lane, 2004). This method however requires sound planning and coordination with the mining team, suitable ground near to the process plant, and the pit from which the embankment construction material can be sourced must be close.

Design for the environment

The business approach adopted by many mining companies was that of 'CAPEX (capital expenditure) is king', followed by OPEX (operating expenditure). In the tailings disposal field this results in the minimum of work being conducted prior to deposition, and deferred capital expenditure with no concept of how to close the facility.

The design for the environment approach should result in tailings facilities that are significantly easier to close with much preparatory work for closure having already been undertaken prior to cessation of mining.

A technology that is of interest to mining companies to this end is that of paste and thickened tailings (Jewell *et al*, 2002). Although this technology is not new, recent improvements in thickener technology and increased environmental pressures have led to a resurgence in interest.

Paste and thickened tailings

Paste and thickened tailings technology is a promising initiative towards achieving intrinsically safe and environmentally responsible tailings disposal. Production of paste or thickened tailings involves the use of thickeners and/or filters to form a viscous, non-segregating material. There are two methods of producing such tailings: high compression or deep cone thickeners can be used or alternatively filters (belt or disc).

High-density tailings disposal has been fairly widely practiced to date and is commonly misinterpreted as being paste disposal. Thickened tailings and paste are terms that are often confused, as there can be some overlap between the two. The boundary between un-thickened and thickened is defined by water content (20-50% solids for the former and 50-70% for the latter). Paste material is typically dewatered to the upper end of the thickened tailings spectrum and usually has no bleed water.

Backfill is typically produced by means of filters with cement and some water added to improve flow properties, thereby assisting distribution by gravity.

The claimed advantages for thickened tailings are improved environmental and safety performance. Thickened tailings facilities, if properly designed and operated, do not have a supernatant pool on the surface of the facility. This is particularly true of the paste materials that exhibit zero bleed of free water. The absence of a pool means that the potential for over-topping or other water-induced failure mechanisms is greatly reduced. The tailings

material is closer to the solid-phase than with un-thickened tailings, which also reduces the potential for stability problems. Similarly the potential for seepage from the facility is lower as the hydrostatic head on the foundation without the pool is significantly less.

The absence of the pool on the facility surface also means that there is potentially lower reagent exposure to the environment and avian and wildlife protection measures are simpler.

Smaller, but possibly significant benefits could accrue through improved reagent consumption via the recycling of process water without exposure to the environment. Similarly metal recoveries could potentially be enhanced slightly through recycling of the water.

With higher deposited densities tailings facilities could, in certain climatic or rise-rate situations, have greater storage capacity providing a longer useful facility life.

Thickened tailings or paste is often used to provide underground support when cemented. In this manner the good practice of waste minimisation is adopted.

The potential disadvantages associated with this technology are that: not all tailings materials are amenable (the percentage finer than 20 microns is important), there is a loss of some of the key geotechnical benefits in terms of strength and permeability, higher capital costs, and transportation difficulties. Other problems are flatter beach slopes, susceptibility to dust generation and slope erosion.

The reduced water content and high solids concentration renders paste viscous resulting in large pressure losses during flow in pipelines. High-pressure pumps are therefore required, typically positive displacement pumps with associated high-pressure pipelines, the costs of which are much higher than for conventional slurry systems. Operating costs of such systems are said to be lower.

3.3.10 Design process

A recognised design process for the closure of tailings facilities adopted by at least two of the leading specialist firm of design consultants is that known as ‘designing with the end in mind’ (Golder Associates, 2003a) and alternately ‘designing inside out and backwards’ (Ulrich, 2004). These two approaches are largely similar in that both methods take note of the fact that one needs to start as early as possible to ensure successful closure and that:

- The behaviour and appearance of the facility should be known before it is built.

- Closure goals and strategies should be established during the design stage.
- The facility should be constructed and operated in a manner that ensures that the closure objectives can be realised.
- Closure goals and strategies should be based on operational experience.

Knight Piésold (Ulrich, 2004) recommend that the following steps be undertaken (Figures 3.3.2 to 3.3.6):

- Establish the geochemical properties of the tailings mass through characterisation.
- Physical characterisation of the tailings mass and wall structure.
- Known properties and behaviour to commence cover design.
- Iterative design process to limit pollutant releases to air and water.
- Environmentally protective cover on which to restore a suitable land use.
- Human health and ecological risk tolerance.
- Regulatory and stakeholder concurrence.

Figure 3.3.2: Flow chart to establish tailings characteristics (Ulrich, 2004)

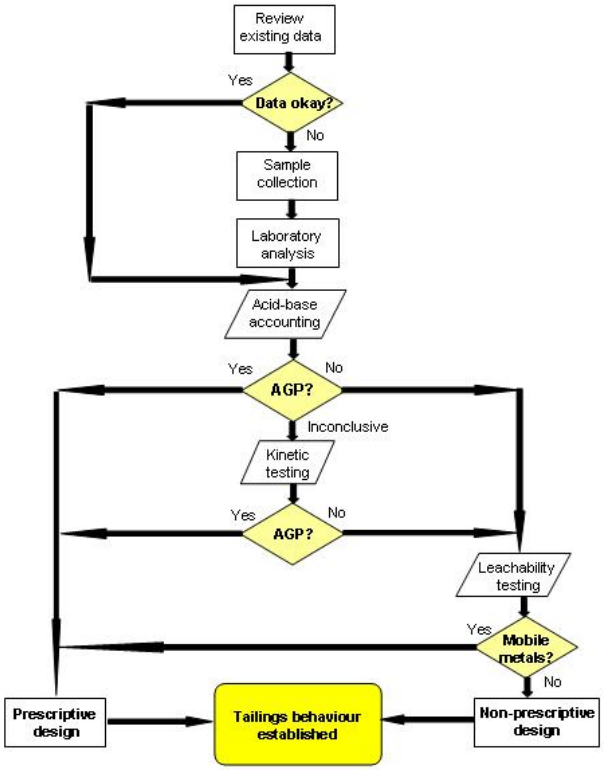


Figure 3.3.3: Flow chart to establish stable tailings mass (Ulrich, 2004)

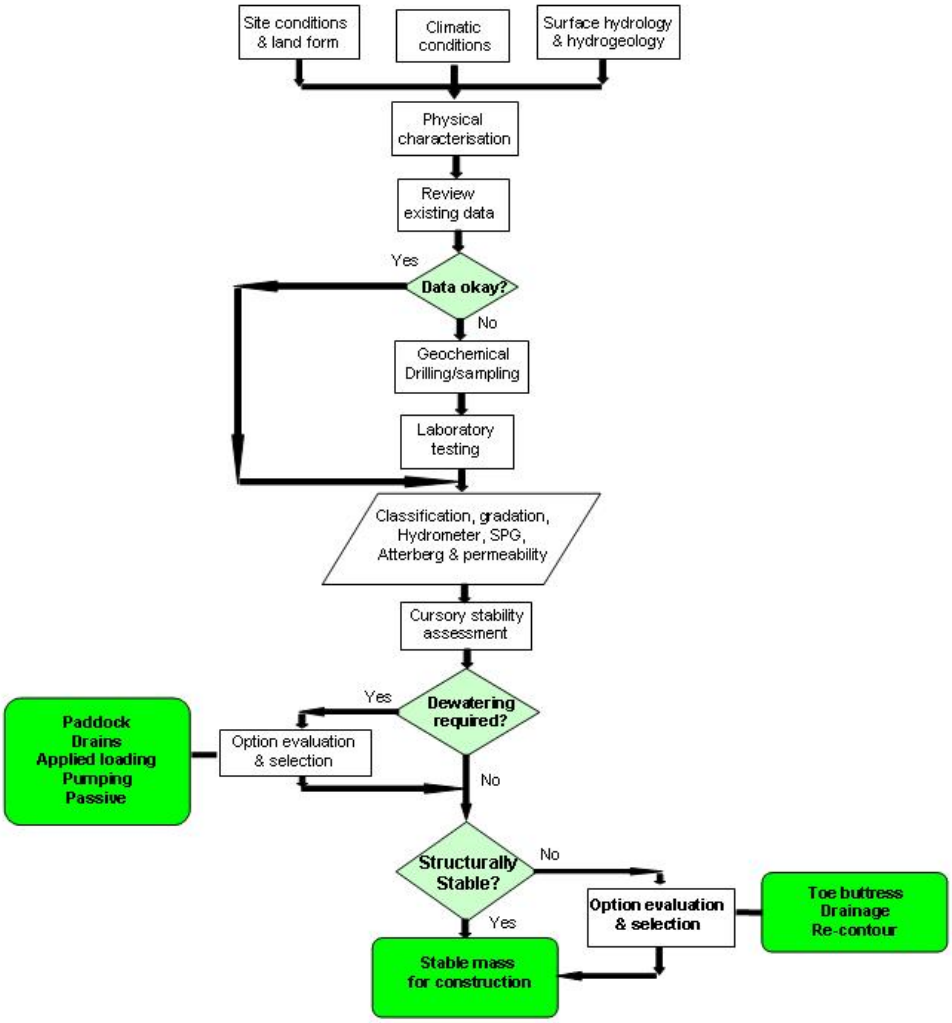


Figure 3.3.4: Flow chart for the cover design process (Ulrich, 2004)

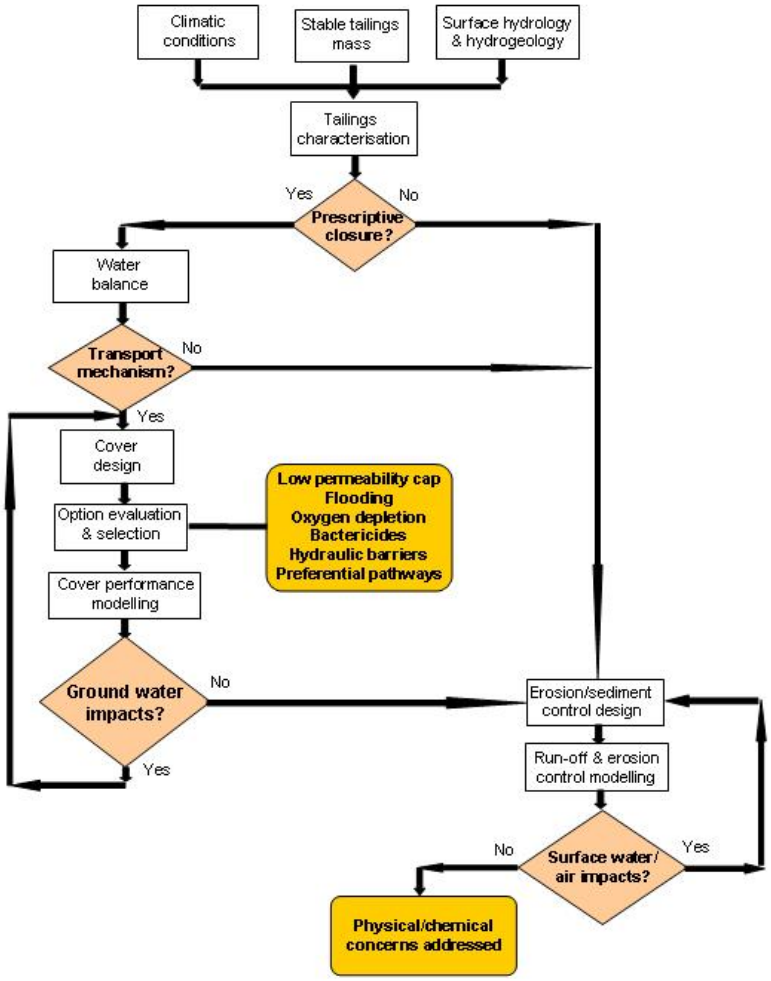


Figure 3.3.5: Flow chart for land use restoration (Ulrich, 2004)

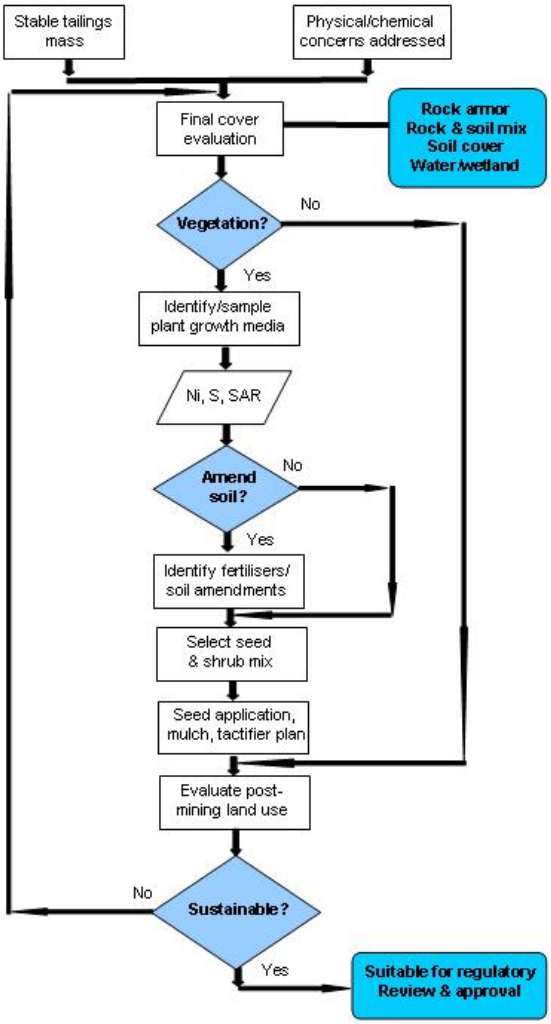
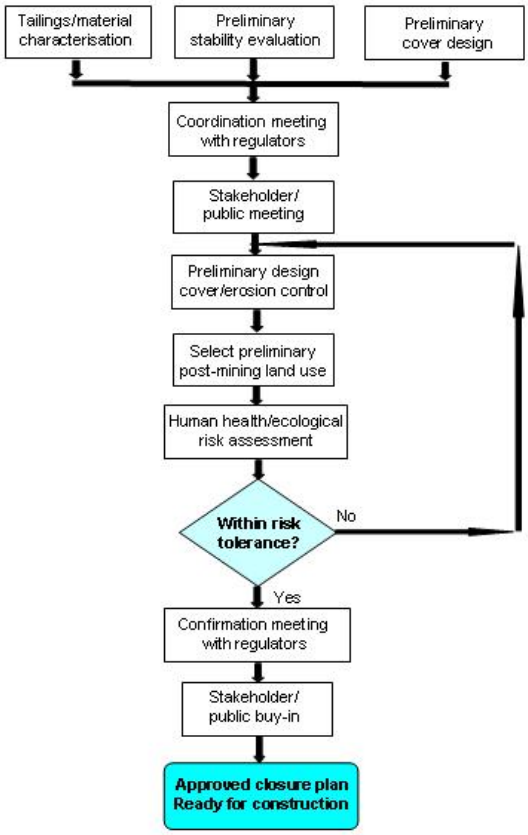


Figure 3.3.6: Flow chart for risk assessment and stakeholder participation (Ulrich, 2004)



3.3.11 Technical details

The technical details adopted for the tailings are vitally important. Those adopted to date are often inappropriate and are not capable of ensuring the long-term sustainability of the closure solution adopted for a tailings facility.

Operational practices

Operational practices significantly influence the relative ease and cost of closure. With this in mind operators should endeavour to minimise the process water sent to facility in the first instance through thickening. This is fundamentally important as even small improvements in the slurry density sent to the facility result in substantially less water discharged to the environment (Figure 3.3.7). At the same time thickening minimises reagent usage in that

more is retained within the metallurgical plant and not discharged to the facility where the reagents are either lost through natural processes or need to be destroyed for environmental protection reasons. An additional spin-off of this approach is that there are also small but significant improvements in mineral recovery rates.

Water conservation

Fresh water is becoming increasingly scarce in many parts of the world due to population growth and misuse, with competition for its use by industry, agriculture and human consumption. The impact on mining, especially in drought-stricken areas of the world, is that water may not be available in sufficient quantities or the costs of water will become prohibitively high adversely affecting the project viability.

Mines are often sited where water is in short supply or there are increasing demands on supply. Some nations have, or are, in the process of implementing regulations that charge for the use of all water, whether it is through direct consumption or indirect use such as loss from evaporation: once these laws are passed, the economics of some operations could change substantially. In some parts of the world it has been possible to discharge water to stream provided that the quality meets certain quality standards. These nations are planning to charge for the pollutant content within the discharged water as a way of incentive for operations to reduce this to the minimum.

Figure 3.3.7: Water & solids content versus slurry density (specific gravity of 2,7t/m^3)

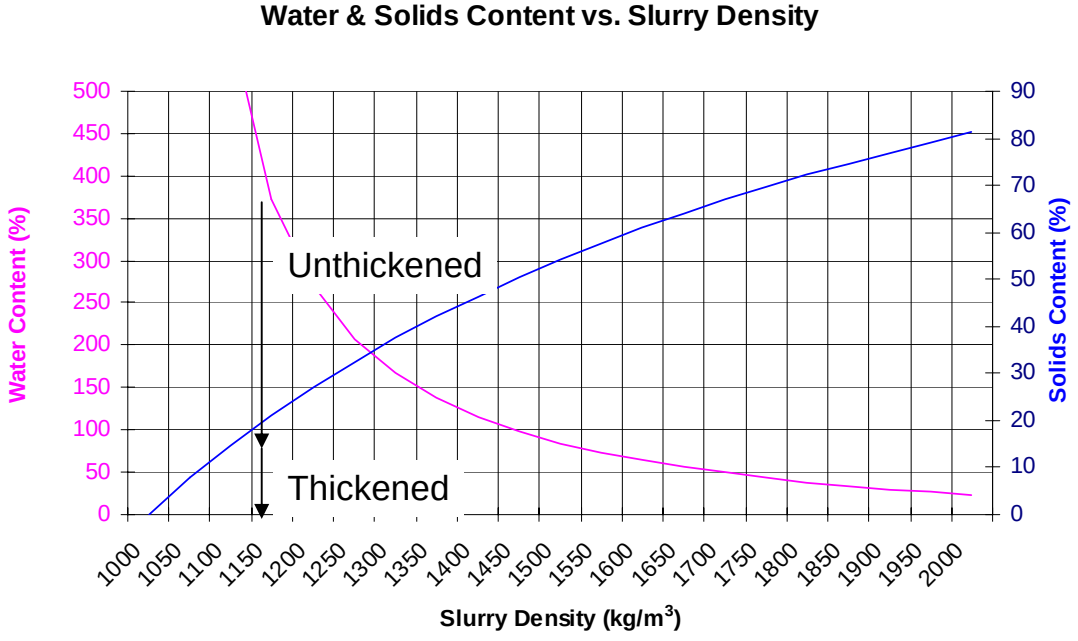
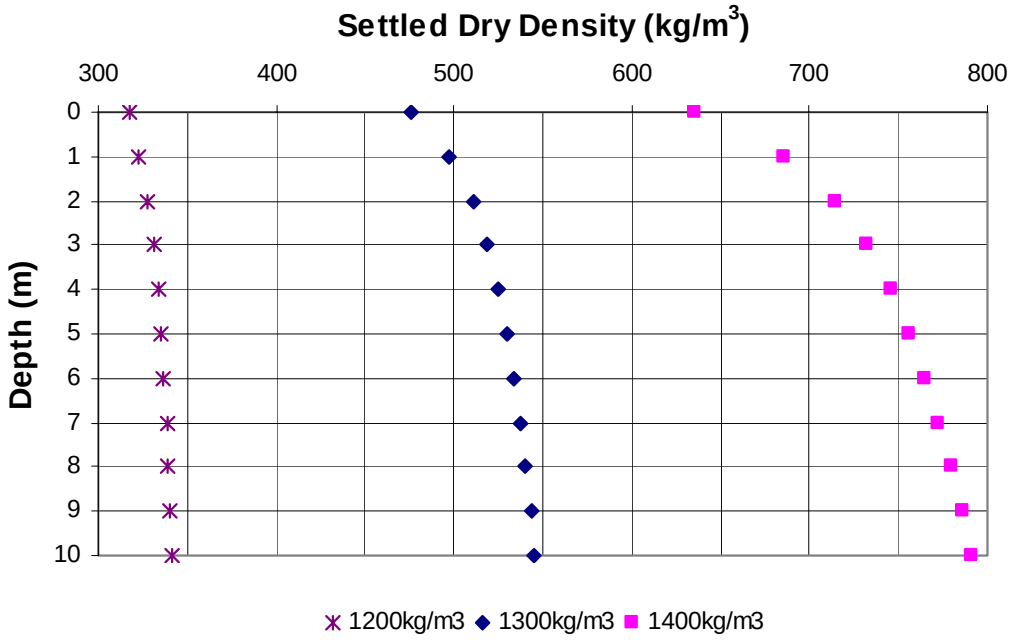


Figure 3.3.7 is a plot of water and solids content against slurry pulp density. It is evident that a relatively small change in the pulp density significantly affects the quantity of water discharged to the facility. The 100% water content threshold approximately denotes the transition between 'un-thickened' or conventional tailings and 'thickened' or high-density tailings. Slurry with a pulp density of 1,15t/m^3 has almost five-parts of water to a one part of solids. Once the pulp density is increased to 1,45t/m^3, the water content reduces to one-part water to one-part solids. This range of pulp density is within the normal range for conventional tailings at most operations. Further thickening obviously has the effect of reducing the amount of water, but at slower rate.

Figure 3.3.8 depicts the hypothetical case where slurry is open-ended into a body of water and the slurry is allowed to settle under self-weight only. Seepage and evaporative losses are not taken into account. This scenario could approximate to the case where slurry is discharged into a water-filled pit. The graph is a plot of slurry settled dry density against depth below surface. It is evident from this graph that the density at which slurry is first deposited is important in determining both the rate and the extent of densification in such circumstances. In other words, slurry of high water content will achieve a lower ultimate dry density than slurry of low water content. This has the important implication that capacity within a facility is effectively lost 'forever' when high water content slurry is deposited directly into the pool.

Figure 3.3.8: Slurry dry density versus depth



Enhanced consolidation through solar evaporation should be encouraged through sub-aerial deposition and well-managed deposition cycles to achieve deposition in thin layers that are exposed to the drying effects of the sun and wind with subsequent filling of consolidation cracks.

Supernatant water should be decanted from the facility as soon as possible and the pool size should be small. The settled densities achieved by deposition into water are significantly lower than for sub-aerial depositions (Figure 3.3.8).

The long-term settlements associated with the slow consolidation significantly delay closure works for access reasons and cause problems of deflection and cracking of the capping layer.

Essentially therefore one should deposit as dry a slurry as possible and minimise the pool area to facilitate sun drying and hence maximise the useful life of the facility.

Energy efficiency

The energy consumed by mining processes is rarely given detailed consideration other than to size motors, or define power supply requirements at project inception. Schemes are generally not compared on the basis of energy efficiency and energy consumption is seldom benchmarked.

The power consumed by a metallurgical plant is heavily influenced by its distance and elevation from the water supply point and the tailings facility. Large amounts of energy are consumed in transporting the slurry to the facility and in returning excess water to the plant for recycling and in importing make-up water.

Clearly the amount of water sent to the tailings facility and the method of transportation contribute significantly to the energy consumed by the metallurgical process. Lower energy consumption means reduced greenhouse gases that translate into improved sustainable practices.

Reagent control and conservation

Lower quantities of reagents should be used for two reasons, namely reduced operating costs and fewer potential pollutants sent to the environment. This could be achieved through higher recycling of process waters at the plant rather than recovery from the tailings facility where the reagents degrade upon exposure.

Metal or mineral recovery

Greater recycling of process water at the metallurgical plant provides the potential for improved metal or mineral recoveries.

Geometry

Straight lines, favoured by engineers for ease of setting-out and construction control reasons, should be avoided and curves adopted in their place. The main reason to avoid curves in closure design is because, as any artist knows, there are few perfectly straight lines in nature. For aesthetical and durability therefore curves are preferable. The difficulty and expense of setting-out and control of non-linear forms should not be underestimated and the potential for concentrated flow mitigated.

Detailed and sufficiently accurate survey information should be obtained prior to closure design. It is especially important for storm water management design that level information is accurate, say to within +/- 200mm or better.

Accurate geometric modelling should be undertaken to assist with the process of endeavouring to balance cut and fill quantities. The consequences of being short or having a large surplus of material could be prohibitively expensive.

The closure design should make adequate allowance for long-term settlements associated with consolidation of the tailings material and settlement of thick fills.

Upper surface profile

The upper surface of the tailings facility should preferably be domed, or in certain circumstances dished but never left with a flat profile. The domed, shedding profile is favoured as this would result in the least amount of seepage from precipitation after closure and would avoid the concentration of salts that could destroy or limit vegetation growth. In some instances the domed profile may not be practical and it may be necessary to form a dished profile. The pool that would inevitably form, at least at times, would need to be accurately modelled to ensure that it could be safely contained at all times in the future and that suitable vegetation be established that could tolerate the conditions that would result. Seepage prevention methods would also need to be considered.

Paddocking or compartmentalisation of the upper surface and other flat areas, such as berms for example, has been attempted to prevent the flow of storm water, but the potential

for over-topping of the paddocks or cells always remains due to siltation or breach of the dividing walls (Free State, Appendix).

Outer slope profile

The outer slopes of the tailings facility should be designed to be significantly flatter than is current typical practice. The overall angle should be flat enough to permit access by mechanised equipment used in vegetation establishment and maintenance operations and should take account of the material that will be used to create the landform being no steeper than could be tolerated by the material.

The slope should be created to the profile required for the closure state during the constructional and operational phases. A reason for this is that efforts directed at achieving the closure condition could be tested during the period at which there are resources readily available and there remains time for experimentation. Another benefit is that the geotechnical risk associated with potential slope instability could be significantly reduced avoiding many of the associated monitoring and remediation costs.

In keeping with the recommendation to avoid straight lines, the slope should be formed in the convex/concave profile commonly found in nature (DME, 1996). Different material types and gradings could be considered for use along different portions of the slope profile, for example coarse material at the convex toe as found in natural scree-slopes.

Special attention should be given to the crest detail as this is very prone to wind erosion (Blight, 2000). Methods of protecting this area could include measures to enhance or reinforce soil integrity and/or dense, wind-resistant vegetation planted right to, and over the crest.

Drainage details

Tailings facility drainage is the most important of the technical details to get right. This is fundamental to the long-term durability of the facility and is often undertaken in a hap-hazard manner using an empirical approach based upon what has been undertaken previously and the available funds.

There are some examples of successful closure of coal dumps in the United States of America and South Africa (Coal Discards Dumps, Appendix) but these have been achieved by great attention to detail with the drainage measures.

Drainage measures should encourage sheet flow down gentle slopes in facilitating the removal of water from the facility and discharged onto the natural ground. Longitudinal berms that include dense vegetation can be used in this instance to break up long slopes and reduce the velocity of surface water flow.

Great care should be taken with drainage measures wherever flows are concentrated. Designers should remember that water will always find the shortest, easiest route even if, as is often the case, it is beneath or along the lined drainage channel of pipe, rather than within it as the designer intended.

Inlet and outlet details are especially important. The installation of shear keys at these points should be considered to prevent water from travelling beneath the drainage channel key.

Closure designs should not include pipes as these are susceptible to blockages and deterioration in time as well as being washed out. Spillways and open channels are preferred.

The use of concrete should be avoided wherever possible as concrete requires maintenance. Permanent closure spillways should be created through natural resilient rock wherever possible.

Drainage systems should be designed to be sufficiently flexible to accommodate movements associated with tailings consolidation and differential movements relating to different settlements of cut and fill sections. Frequent movement joints are recommended but these should be designed to be durable.

Surface stabilisation

Surface stabilisation should be achieved via a living, self-sustaining cover. This usually involves the establishment of a sustainable vegetative cover in amenable climates. The cover should be as ecologically diverse as the ambient climatic conditions and situation permit.

Vegetation establishment requires a soil cover or growth medium that should generally be no thinner than 500mm and based upon the length of the longest roots of the vegetation used to bind the soil to provide an adequate rooting horizon. This horizon should have the ability to retain sufficient moisture to support vegetation growth without allowing a downward movement of excess water to move into the underlying tailings and cause seepage.

Since vegetation spatial patterns are related to competition for water and the aridity of the soils (von Hardenberg *et al*, 2001) it may be possible to make use of spatial patterns as part of landform design. For example, 'islands' of vegetation could be used to manage water and air flow and therefore erosion. Electro-magnetic investigatory methods could be used to obtain information on the underlying hydrology to determine the spatial sub-surface flows that would influence vegetation growth for design purposes.

The capping layer should be formed from soils that posses the required properties to meet the intended function. Covers of well-graded material, for example waste rock and topsoil mixtures, appear to be particularly successful in a wide variety of conditions (ERGO, Appendix). This is attributed to such materials being significantly less prone to erosion than poorly graded materials, such as clean sands or cycloned underflow for example. A further benefit is that the larger particles tend to protect the roots and facilitate the retention of water underneath.

An important part of any vegetation cover is grasses but these should not be used alone as they do not bind the soil fabric: other plants such as alfalfa should be used in addition for this function and also to fix nitrogen in the soil.

Trees and shrubs are generally avoided in situations where the roots could interfere with the structural integrity of the facility such as on the impoundment walls or adversely affect the growth of the key binding vegetation.

It is essential to keep feral goats off the vegetation as they withdraw the roots when feeding thereby destroying the surface stabilisation.

Techniques such as the holistic cattle reclamation method (Savoy Center, 2004) could be considered to obtain a living, self-sustaining cover.

Capillary breaks

Capillary breaks are necessary where the tailings material contains salts that could be drawn up into pores of the growth medium adversely affecting plant growth. Capillary breaks are usually formed from two contrasting soil types, such as a gravel layer over a finer soil layer, to utilise the differences in pore-size distributions and the corresponding differences in capillary (suction) forces under unsaturated conditions to retain water in the upper soil layer (US Department of Energy, 2000).

The properties of the material used to form the break need to be understood and the material placed and compacted under the correct conditions and moisture content to avoid shrinkage cracks. Degradation of the clay under acidic conditions should also be considered. The potential problem with synthetic liners is that their long-term durability is unproven.

3.3.12 Problems with developing closure criteria

The process of developing the correct closure criteria has a number of potential problems. Probably the most difficult issue to address is that of meeting community expectations as it is impossible to satisfy everyone all of the time. What is desirable for one person may be unacceptable to another. The 'perception-is-reality' syndrome is particularly difficult to deal with and to correct.

Other potential problems are:

- Technological limitations.
- Lack of suitable analogue or reference sites.
- Understanding of seasonal processes.
- Management issues.
- Monitoring issues.

Closure criteria should be reviewed regularly to include new research findings or operational practices.

3.4 Measuring Success

3.4.1 Measurement techniques

One of the greatest difficulties encountered with closure is that of demonstrating success and it is even harder to predict future performance with certainty. To date most closure works have been judged in a largely subjective manner with the focus upon measuring biodiversity as the key indicator of suitable closure. Predictions of future long-term performance are typically made without sound scientific basis or comparison of actual trends with predicted performance with time. The result of this uncertainty is reluctance on the part of the regulators to accept closure activities, certainly in the early stages after closure. The mining industry, on the other hand, is keen to fulfil its obligations, removing liabilities soon after mining operations have ceased. This current situation is typically one of impasse with the mining companies unwilling to undertake work that might never be approved and the regulators not accepting closure work in the absence of proof of success.

Success can only be measured and therefore demonstrated via a formal process of comparison of the performance of the closed tailings facility in terms of the key closure criteria, as discussed previously, at regular intervals during the facility life. The measurements can then be compared with predictions of performance to demonstrate trends. A technique developed for this purpose is Ecosystem Function Analysis (EFA) developed by CSIRO (Lacy *et al*, 2001). This technique uses indicators to evaluate the development of ecosystem function over time permitting comparison with analogue sites, these being reference sites selected from a range of undisturbed sites considered to be representative of the area prior to mining. EFA was designed to be simple, rapid and applicable to areas in a wide range of ecosystems and has significant advantages but some important limitations.

The EFA field procedure comprises three components, Landscape Function Analysis (LFA), vegetation dynamics and habitat complexity. LFA measures the key ecosystem processes of soil stability, water infiltration and nutrient cycling and involves dividing the landscape into strata or landscape zones and conducting soil surface condition assessment for each zone. Scores are grouped to form three indices of soil quality that measure the: ability of the soil to withstand erosive forces and reform after disturbance; how the soil affects the amount of water that runs off or infiltrates; and how efficiently organic matter is recycled into the soil. The vegetation dynamic module was designed to provide information about the condition of the vegetation recording information on plant cover, density and species composition. The fauna habitat module uses habitat complexity as a measure of faunal habitat value by assuming that good correlations exist between this and faunal diversity.

EFA is largely theoretical with little practical application to date but has some potential. It is a technique that could be used to demonstrate progress towards an end goal giving early evidence that closure solutions are headed in the right direction. It is plausible that regulators might accept the evidence provided by such a technique for early signoff when combined with other techniques to demonstrate the sustainability of a site and meeting its land use objectives.

The main limitations of EFA relate mainly to management aspects in terms of:

- Issues related to scale of observation. This could be mitigated to a large extent by conducting field trials that are essentially the ‘pilot plants’ in engineering terminology.
- Detecting and assessing temporal changes.
- Constraints of managing tailings hydrology.

3.4.2 Indicators of success

The effectiveness of ecosystem rehabilitation measures could be ascertained by interpretation of EFA indicators. Success would be indicated when:

- The regression between the LFA index and the measured variable has a high statistical relationship over a range of indicator values with few outliers.
- The relationship is linear implying that the indicator's sensitivity to environmental change is similar throughout the indictor range.
- Data acquired from rehabilitated site and analogue or reference sites should occupy the same data space indicating that the index numerical value has the same meaning throughout a given mine site.

The use of reference as opposed to analogue sites is recommended as the former provides better definition of the realistic closure objective. Analogue sites are probably invalid as mining has disturbed the area and attaining the same state as the analogue site may be impossible.

When considering indicators of success it should be remembered that the current methods of assessment are based upon point observation methods. Methods that probe soils at a larger scale relevant to the overall behaviour are required. Current methods largely ignore uncertainty and risk. Risk-based approaches should therefore be developed and adopted.

3.4.3 Process to demonstrate sustainable closure

The key elements of a process to demonstrate sustainable closure are outlined as follows:

- Self-certification at various stages of completion supported by monitoring data and rehabilitation inspection checklists.
- A formal process of comparison of the performance of the closed tailings facility in terms of the key closure criteria.
- Demonstration of progress and success towards the end-goal with evidence that the closure solution has outcomes that are headed in the right direction.
- Independent audits of rehabilitation.
- Certificate of completion.

3.4.4 Monitoring techniques

Suitable monitoring techniques that enable regular assessment of progress towards attaining the predefined closure goals should be implemented and maintained for a sufficiently long

period after closure. The techniques should permit the testing of all key elements that combine to result in a sustainable situation.

Financial

The rate and manner in which financial resources are being consumed needs to be monitored to ensure that there are adequate funds until the end goal is achieved. Actual financial expenditure should be compared to planned expenditure at regular intervals during the project.

Social

Social factors need to be monitored to ensure that the closure solution is resulting in the desired quality of life.

Factors that impact upon the social environment include aesthetics from a degraded landscape or obstructed views.

Quality of life could be impacted through land sterilisation or interrupted access or many other ways identified by the EIA and stakeholder consultative processes.

Air quality

Air quality in the vicinity of tailings facilities can typically be degraded by harmful gaseous emissions, airborne dust, or unpleasant odours.

Sampling of dust is usually undertaken by collections from buckets installed at points around the tailings facility. This approach has the significant disadvantage, particularly after the mine closure phase that the buckets can be stolen leading to a loss of data.

It has been understood for some time that the disappearance of lichens can be linked to air pollution (Fischer, 2003). The use of lichens as an indicator of air quality has become established practice in some instances, made possible by the lichens' pollutant bioaccumulation ability, lack of an exclusion mechanism and their susceptibility to heavy metals. Without an excretion mechanism foreign matter cannot be expelled from the lichen and accumulate over the years. Data could therefore be used to provide integrated measurements over a long period of up to ten or twenty years. Lichens provide an effective method of air pollution monitoring since: many species are widely distributed and grow in a range of habitats, can be surveyed all year round, lichens lack a cuticle and root system and obtain all nutrients as particles in solution directly from atmospheric deposition, comparisons

can be made with samples from herbarium specimens or specimens from uncontaminated analogue or reference sites enabling retrospective analysis of pollution, and the ability of lichens to accumulate elements in very high concentrations aids chemical analysis and facilitates the detection of elements present in very low concentrations in the environment.

Water quality

Surface and subsurface water quality in proximity to tailings facilities can typically be degraded by seepage or polluted run-off which has the potential to impacts large areas outside the original mining zone.

Water quality is usually monitored via ground water monitoring wells and sampling points in watercourses for surface water flow. The technical literature covers this topic extensively (Bibliography).

Soil quality

Natural indicators, such as indicator plants to highlight nutrient deficiencies, and earthworms and organic matter content to demonstrate growth medium health, should be considered.

3.4.5 False indicators of success

Apparent early signs of success could readily be misinterpreted. High biomass for example could be mistaken as a sign that vegetation establishment would be sustainable in the long-term. Higher biomass (very high density vegetation), than the surrounding area could however be an indication of the vegetation obtaining additional water from rainfall alone probably from the tailings material before it has dried fully. An example of this is the vegetation establishment trials at Boddington (Appendix). The large water consumption would be associated with deep root exploration within the tailings since biomass density has an almost directly linear relationship to water availability. As the tailings dries after closure vegetation would need to change and thin out changing the stabilisation characteristics. Furthermore compaction would occur as the tailings material dries adversely affecting the success of vegetation.

3.4.6 Technical issues to be addressed prior to sign-off

The following technical issues should be addressed prior to signoff:

- Stability and erosion.
- Nutrient limitations.
- Salinity, pH and metal toxicity.

- Other soil limitations.
- Unexpected seasonal climatic conditions.
- Senescence.
- Recruitment.
- Insect attack.
- Inability to withstand fire.
- Inability to withstand drought.
- Failure to meet designated land use objectives.
- Uncertainty regarding long-term sustainability.

3.5 Tailing Facility Closure Rules

Tailings facility closure rules for success are presented in the following sections. The rules are divided into three categories, namely rules for mining companies and owners, rules for regulators, and rules for guardians of social equity and ecological equity.

The closure rules contain some additional guidance that should be followed as a minimum to ensure the success of a closure project.

These rules and guidance for the decommissioning and closure of tailings facilities are generic and endeavour to protect human health and the environment.

3.5.1 Rules for mining operators and owners

Mining companies should consider the following rules and the associated guidelines when planning or executing tailings facility closure.

Rule 1:

Embrace a new mindset (do it properly or not at all).

Guidance

- Embrace a new mindset to avoid the thinking of the past that led to today's problems.
- Adopt the ICMM ten principles for sustainable development (ICMM, 2003).
- Avoid half-hearted attempts that are a waste of valuable resources.
- Adopt holistic management principles where goals are set, plans are made and progress towards attaining the goals are monitored whilst making decisions that simultaneously consider economic, social and environmental realities.
- Ensure a concerted, properly managed and integrated team effort.

- Examine new financial accounting methods that avoid the current NPV approach that misleadingly indicates that it is financially preferable to delay closure to the end of the project life.

Rule 2:

Adopt the 'design for the environment' approach.

Guidance

- Design for closure right from the start with the end in mind and consider closure issues at project inception and re-evaluate throughout the life-cycle.
- Follow the recommended design process which is to:
    - Ensure that storm water drainage measures are appropriate and durable.
    - Understand the final landform.
    - Manage closure from the outset by setting and maintaining the correct standards and not rely upon remedial measures to rectify an inappropriate design.
- Minimise tailings generation.
- Examine and implement new methods of deposition to provide a tailings disposal solution that is possible to close in a sustainable manner.
- Endeavour to remove pollutants from the tailings stream at source rather than sending them to the environment and having to deal with them there and keep potential pollutants separate.
- Permanently fix potentially toxic pollutants in cemented backfill or by similar techniques where appropriate.
- Ensure that the tailing facility does not degrade the ambient environment and does not inhibit the ability of future generations to live at similar standard.
- Adopt technical details that assist with closure.
- Develop a framework for tailings facility closure based upon detoxification at source.
- Establish the optimum after-use alternatives.
- Consider the potential to turn liabilities into assets, for example, the sale of valuable land after rehabilitation.
- Prepare an initial closure plan.
- Prepare a closure and aftercare estimate.

Rule 3:

Establish environmental baseline data and analogue/reference sites.

Guidance

- Compile and maintain a good database that includes all pertinent data during all tailings facility life-cycle phases.
- Obtain baseline date wherever possible.
- Identify and monitor analogue sites that represent the area prior to tailings deposition.
- Identify reference sites that represent the area after tailings deposition and successfully rehabilitated.
- Ensure the certainty of outcomes supported by good quality factual information.

Rule 4:

Follow a risk-based approach that includes re-evaluation of tailings facility-related risks that may be present upon cessation of operations.

Guidance

- Adopt a risk-based design approach that includes:
    - Identification of hazard.
    - Preparation of preliminary design concepts.
    - Assessment of risks associated with the concepts.
    - Modification of design to address high risk areas.
    - Re-evaluation of risks, including development of a risk management plan.
    - Finalisation of design and implementation.
    - Ongoing design, monitoring etc.
    - Consideration of risk of premature and unplanned mine closure.
- Conduct SEA.
- Conduct EIA.
- Reconsider tailings facility decommissioning approximately two years prior to termination of the metallurgical plant operation.
- Draft a method statement that defines the manner in which the facility is to be closed.
- Physically cut all mechanisms for delivery of tailings to the facility to prevent further discharge of tailings or process water onto the facility surface.
- Ensure that adequate storm water removal measures are in place.
- Re-assess the long-term environmental, health and safety risks posed by the facility after closure to facilitate the final closure design process.
- Consider the potential impacts of system failures, for example closure criteria not being met, changes in legislation or social pressures.

- Reconfirm aftercare requirements.

Rule 5:

Develop site-specific closure criteria.

Guidance

- Define strategic objectives from the SEA process.
- Ensure that the closure criteria are site specific.
- Take cognisance of the ambient climatic conditions and consider extreme climatic events.
- Consider views and involve all stakeholders.
- Consider potential changes in future requirements.
- Consider the potential for the tailings to be a future resource that could be re-mined at in the future.
- Consider social issues.
- Meet end land-use objectives.
- Integrate closed facility into ambient landscape.
- Limit facility erosion rate to no faster than that of the surrounding natural topography.
- Set measurable outcomes.
- Never assume that a 'walk away solution' is possible.

Rule 6:

Plan and implement procedures to manage storm water run-off and solutions from the tailings facility with the objective of protecting human health and the environment.

Guidance

- Employ suitably qualified and experienced professionals to design the closure profile and condition.
- Maintain hydraulic separation between the tailings mass and the underlying or adjacent surface and ground water resources.
- Prepare construction drawings and as-built records once the work is complete.
- Include any necessary updates of the environmental modelling to re-predict the long term after closure behaviour for monitoring purposes and anticipate the probable maximum flood and earthquakes, where applicable, ensuring that the facility would be capable of sustaining these extreme events as considered during the design phase and reconfirmed during the closure design phase.

- Determine capping and cover requirements after consideration of the geochemical nature of the tailings and the environmental conditions that the facility would be exposed to in the future.

Rule 7:

Ensure a reduction in environmental liability throughout the life of the mining operation through operating for closure, progressive rehabilitation and footprint minimisation.

Guidance

- Pre-strip and stockpile suitable topsoil prior to tailings deposition for use in rehabilitation efforts.
- Dewater tailings as far as can reasonably be achieved prior to deposition to minimise the quantity of water used and the reagents sent to the environment.
- Adopt sub-aerial deposition techniques to accelerate consolidation of the tailings where appropriate.
- Commence rehabilitation works during the operational phase wherever possible.
- Recover and recycle process waters from the tailings facility.
- Incorporate suitable environmental protection measures.

Rule 8:

Prepare final closure plan.

Guidance

- Prepare the final closure plan and update cost estimates a few years prior to facility closure.
- Return the facility to a viable post-mining land-use.
- Create a living system.
- Make allowance for limited historical data sets and also for uncertainty around the global-warming issues and the potential impact of climatic extremes.
- Apply BATNEEC to achieve a closure condition that is as close to a state that is as maintenance-free as possible.
- Construct the final facility configuration to ensure that the outer face profile remains stable and is no more prone to wind and water erosion than the natural ambient topography.

Rule 9:

Control the releases of potential pollutants from closed facilities to protect human health and the environment.

Guidance

- Control deleterious releases from the tailings facility via suitable means for as long as necessary after closure to prevent degradation of human health and adverse environmental impacts.

Rule 10:

Provide financial assurance for the closure of tailings facilities, within mine reclamation (rehabilitation) planning activities consistent with political jurisdictional requirements.

Guidance

- Make adequate provision during the operational life of the mine to cater for the costs associated with tailings facility closure.
- Ensure financial ability to undertake closure work.
- Endeavour to obtain appropriate reductions in the magnitude of financial guarantees based upon company's track record of closure success.
- Consider realistic closure, care and maintenance costs at project inception and revisit regularly throughout the life-cycle.

Rule 11:

Provide closure management system.

Guidance

- Prepare and implement a comprehensive tailings management system for the full facility life-cycle.
- Define all responsibilities.
- Ensure continuity.
- Manage and document changes.
- Prepare and update operating procedures and manuals.
- Ensure proper supervision of all phases.
- Undertake all aspects of tailings management, from the pre-feasibility to decommissioning phases with closure in mind and as the goal.

Rule 12:

Implement a monitoring and aftercare programme to confirm that procedures and controls are effective.

Guidance

- Specify the monitoring and aftercare requirements during the closure design phase.
- Make the necessary provision for ongoing repair and maintenance.
- Prepare comprehensive reports that present the facility condition and the results of the environmental monitoring.
- Compare the results of the monitoring with the predicted results to demonstrate the closure activities are achieving the desired effect.
- Ensure that monitoring plans conclusively demonstrate that the objectives have been met.
- Conduct independent audits.
- Formally compare progress against predicted or modelled progress.
- Continually check to ensure that the closure plan is being adhered to and that implementation is effective.
- Monitor sustainability indicators that include community sustainability.
- Conduct EIA on the post-closure condition.

Rule 13:

Conduct transparent reporting.

Guidance

- Keep stakeholders informed.
- Undertake factual, concise and honest reporting.
- Conduct all closure processes in a transparent manner to foster trust thereby facilitating future permitting processes.
- Maintain and present comprehensive environmental and financial data with detailed and accurate information to demonstrate success and provide a database for future closure projects.
- Review successes and failures to achieve continual improvement.
- Broadcast successes to renew the social license to operate.

Rule 14:

Encourage and support research and development into tailings closure issues.

Guidance

- Undertake research and trials to prove techniques to demonstrate that closure objectives can be achieved.
- Encourage and support research and development to find new ways of avoiding and dealing with closure problems and that cater for more stringent conditions in the future.
- Promote integrated approaches that cover soil science, ecology, hydrology and geomorphology in rehabilitation research.
- Support research into marine and lake tailings deposition.

Rule 15:

Listen to non-governmental organisations, community groups and concerned individuals.

Guidance

- Listen to the concerns of non-governmental organisations, community groups and concerned individuals.
- Endeavour to address their concerns to maintain the social licence to operate.
- Manage expectations.

3.5.2 Rules for regulators

Rule 1:

Develop and implement legislation to encourage new mindsets and act as a catalyst for change.

Guidance

- Develop few, clear and appropriate legislation and regulations.
- Develop interim indicators of acceptable closure strategies.
- Establish appropriate, rigorous performance standards.
- Ensure that legislation is effective and therefore acts to inspire industry, community and market confidence.
- Protect the interests of the community.
- Endeavour to guarantee the correct closure and post-closure environmental performance of mines without transferring unnecessary and excessive costs to society.
- Ensure that the legislation and regulations do not create new problems.

Rule 2:

Clearly define closure requirements.

Guidance

- Establish the required closure procedures and processes.
- Clearly define the minimum closure requirements and standards without restricting innovation.

Rule 3:

Enforce legislation to ensure that all mining companies are forced to achieve the same standards.

Guidance

- Ensure that regulators have staff of the required calibre and in sufficient numbers for effective oversight and enforcement to ensure performance standards are met as regulation is useless without adequate policing.
- Review performance and monitor impacts.
- Ensure that closure standards are met.
- Penalise mining companies with poor closure track records.
- Determine the marginal cost of pollution to establish the penalties at effective levels.

Rule 4:

Provide incentives that reward successful closure.

Guidance

- Provide incentives that reward successful closure.
- Reward mining companies with good closure track records.
- Ensure that tax arrangements are in place to off-set the negative financial impact of providing financial guarantees.
- Determine the marginal cost of pollution to establish the rewards at effective levels.

Rule 5:

Guide mining companies in achieving closure standards.

Guidance

- Review proposals.
- Provide guidance to assist mining companies with the closure process.
- Grant approvals where appropriate.

Rule 6:

Regularly update regulations.

Guidance

- Regularly update regulations to encourage and accommodate performance improvements.

Rule 7:

Maintain independence.

Guidance

- Avoid being a stakeholder in the mining venture as community and market faith in regulations can be eroded when this occurs.

Rule 8:

Listen to non-governmental organisations, community groups and concerned individuals.

Guidance

- Listen to non-governmental organisations as regulations drafted without community input lack community support.

3.5.3 Rules for guardians of social equity and ecological integrity

Rule 1:

Monitor legislative progress towards ensuring sustainable closure practices.

Guidance

- Monitor legislative progress towards ensuring sustainable closure practices by legislators.

Rule 2:

Monitor mining company progress towards ensuring sustainable closure practices.

Guidance

- Monitor mining company progress towards ensuring sustainable closure practices.

Rule 3:

Apply pressure where and when necessary to encourage sustainable closure practices.

Guidance

- Apply pressure where and when necessary to encourage sustainable closure practices.

Rule 4:

Maintain a realistic and balanced view.

Guidance

- Accept and be transparent in reporting to society that the increased costs associated with improvements to tailings disposal and closure practices would be ultimately passed on to the consumer and society.
- Consider mechanisms for cost transfer associated with the application of higher standards in developing nations to avoid situations where development does not take place because of the increased costs.

APPENDIX - CASE STUDIES

This appendix contains synopses of tailings or other mining-related facilities that were examined to determine current closure methodologies and identify elements or approaches that are likely to be sustainable. The case studies, from around the world, have been categorised and sorted in accordance with the four tailings disposal solutions described in section 3.2.2 (Alternative solutions considered). Although the majority of the examples are gold tailings facilities from AngloGold Ashanti, cases are included from other mining companies and different minerals, namely diamonds, copper, coal, limestone and kaolin. The case studies are considered to be representative as a result of the diverse nature of the AngloGold Ashanti operations with their wide geographical spread and different ownership histories.

BASE CASE:
BIBIANI
BODDINGTON
CÓRREGO DO SÍTIO
EAST RAND
FREE STATE
IDUAPRIEM
JERRITT CANYON
MORRO VELHO
NAVACHAB
OBUASI
SADIOLA HILL
SERRA GRANDE
SIGUIRI
TASMANIAN EXAMPLE
WEST WITS

ENCAPSULATION CASE:
BIG SPRINGS
CERRO VANGUARDIA
COAL DISCARDS DUMPS – KWAZULU NATAL & WITBANK
ERGO DAGGAFONTEIN
GEITA
MORRO VELHO
NORTH AMERICAN EXAMPLES A & B
ROBINSON

DETOXIFICATION CASE:
MANTOS DE ORO – LA COIPA
MORRO VELHO
SUNRISE DAM
THICKENED TAILINGS EXAMPLE

ALTERNATIVE CASE:
BROCK'S CREEK
BUTCHART GARDENS
EDEN PROJECT
IDUAPRIEM
PASTE EXAMPLE
TANAMI
UNION REEFS

APPENDIX – CASE STUDIES

(BASE CASE)

BIBIANI

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Ghana.

Climate: Tropical warm and humid. MAP: 1.500mm MAE: 1.500mm.

Nature of mine residue: Waste overburden and rock.

Area rehabilitated: Waste rock dumps.

Rehabilitation objective: Re-forestation of mined-out areas and waste rock dumps for environmental protection.

Rehabilitation earthworks:

- Capping layer comprising topsoil and fine waste overburden.
- Reshaping of slopes.

Revegetation: Planting of saplings in capping layer. Type of timber species planted: *Millicia excelsa (Odum), Albizia zygia (Okoro), Enlandrophragma anglensis (Adinam), Celtis wightil (Esa), Ceiba pentandra (Onyina), Pterygota macrocapa (Kyereye), Terminalia superba (Ofram).*

Timing: Date of planting May and June 2002.

Erosion control: Some re-shaping of slopes and re-forestation.

Learning points:

- Ease of vegetation establishment in amenable climatic zone.
- Value of enthusiastic and dedicated team.

BIBIANI (CONTINUED)



Re-forested area – pits and waste rock dump.



Pit area prior to rehabilitation.



Slope re-profiling and application of capping layer to provide a growth medium. Capping layer comprises topsoil and fine waste rock.



Saplings planted in prepared area.

BIBIANI (CONTINUED)



Mine nursery.



Results of the re-forestation programme.



Dense growth showing good progress towards achieving desired closure objectives.



View of re-forested area at its extremity.

BODDINGTON

Mineral mined: Gold – bauxite at neighbouring operation.

Mining company: AngloGold Ashanti Australia/Newmont/Newcrest.

Location: Southwest of Western Australia.

Climate: 'Mediterranean', MAP: 600mm winter maximum MAE: 1.400mm.

Nature of mine residue: Fine tailings.

Area rehabilitated: Trial sections of the tailings facility basin.

Rehabilitation objective: Vegetation establishment trials during care-and-maintenance period whilst decision is made on Boddington Expansion Project study.

Rehabilitation earthworks: Nil to date.

Timing: Vegetation establishment trials conducted during the current care-and-maintenance period.

Erosion control: No special measures at this stage. Outer wall slope profiled in benches with back-slope and down-chutes.

Other details: Down-chutes on outer slopes washed out in less than two years since plant decommissioning. New down-chute detail adopted to prevent wash-outs.

Learning points:

- Conducting rehabilitation trials as soon as possible.
- Early results from rehabilitation trials could be misleading in that moisture conditions on tailings facility are typically different to the situation long after decommissioning.
- Proper erosion control measures especially on the outer face of the impoundment wall.

BODDINGTON (CONTINUED)



Tailings facility basin area with adjacent trial area of vegetation establishment.



Vegetation establishment trial area showing more dense cover than adjacent Jarrah forest as a result of water within the tailings. This vegetation is expected to thin out once the high water demand has been exhausted.



Excavation through topsoil layer and tailings showing depth of root penetration.



The native Jarrah forest immediately adjacent to the tailings facility trial section.

BODDINGTON (CONTINUED)



Washed out down-cute on outer face of impoundment wall prior to impoundment wall re-profiling.



New down-chute inlet detail on impoundment wall bench.



Typical impoundment wall profile – note the benches with back-slope to avoid water flow over bench crest.

CÓRREGO DO SÍTIO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Minas Gerais, Brazil.

Climate: Tropical with moderate temperatures. MAP: 1.500mm MAE: 800mm.

Area rehabilitated: Pit slope rehabilitation.

Rehabilitation objective: Stabilise pit slopes.

Rehabilitation earthworks: Benches and berms formed during mining operations – no further rehabilitation earthworks post mining.

Revegetation: Grass establishment via the use of grass mats fixed to soil and rock slopes.

Erosion control: Vegetation establishment on benches and berms.

Learning points:

- Innovative use of grass mats for vegetation establishment – potential application elsewhere and on tailings facility slopes.
- Use of local sub-contractors to assist with rehabilitation efforts.
- Relative ease of vegetation establishment in amenable climatic conditions.

CÓRREGO DO SÍTIO (CONTINUED)



Pit slopes prior to rehabilitation.



Pit slopes during rehabilitation efforts.



Closer view of pit slopes rehabilitation.



Pit slope failure.

CÓRREGO DO SÍTIO (CONTINUED)



Rehabilitated pit slope with Atlantic forest on undisturbed slopes.



Close-up of grass mats – nylon lattice net hand-tied to support the interwoven grass.



Grass mat anchor point at the top of the pit slope.



Rolled-up grass mat at the top of the pit slope.

EAST RAND

Mineral mined: Gold.

Organisation: National Roads Department.

Location: East Rand near Johannesburg, South Africa.

Climate: Highveldt. MAP: 600-700mm MAE: 1.500mm.

Nature of mine residue: Reprocessed metallurgical plant tailings.

Rehabilitation objective: Stabilise excavated slope.

Revegetation: Grass establishment within pockets of soils within concrete 'blocks'.

Timing: Excavation through disused slimes dam to accommodate highway alignment.

Erosion control: Biotechnical rehabilitation.

Learning points:

- Civil engineering technology has potential application in tailings facility closure given that slope erosion is one of the biggest challenges.

References: Swart (2004).



Biotechnical rehabilitation of excavation through a slimes dam.

FREE STATE

Mineral mined: Gold.

Mining company: Anglo American Corporation of South Africa – Gold Division.

Location: Welkom, Free State, South Africa.

Climate: Summer rains, chilly winters and sunny. MAP: 560mm.

Nature of mine residue: Metallurgical plant slimes.

Area rehabilitated: President Steyn PS6 Slimes Dam.

Rehabilitation objective: Slimes dam closure research.

Rehabilitation earthworks:

- Formation of paddocks on the upper surface (basin) of the slimes dam to prevent the accumulation of water in one location and to encourage evapo-transpiration.
- Formation of back-slope on benches and cross-walls to prevent flow along benches.
- Chemical amelioration of slimes to create correct conditions for vegetation establishment and growth and to cater for high sulphur levels.

Revegetation:

- Establishment of grasses directly into the slimes material.
- Use of pioneer vegetation such as wheat to facilitate establishment of desired and sustainable grasses.
- Irrigation of vegetation during the initial stages.

Timing: Rehabilitation commenced after slimes dam was decommissioned.

Fauna: Installation of perches for predatory birds to control rodents.

Erosion control: Vegetation and paddocks to retain water.

Learning points:

- Difficulties of vegetation establishment associated with transition from alkaline to acidic conditions.
- Difficulties associated with vegetation establishment in harsh climatic conditions and different conditions on each slimes dam face.
- Very difficult to establish vegetation on steep slopes.
- Research project proves a scientific approach towards rehabilitation.
- Expertise and experience are broadened by co-operation with government departments and companies with a scientific approach.
- Rehabilitation on gold mine tailing storage facilities can be implemented more successfully with a higher degree of sustainable cover.

References: NH Theunissen (personal communication).

FREE STATE (CONTINUED)



Aerial view of the President Steyn PS6 slimes dam showing the paddocks on the upper surface and the vegetation establishment trials in the perimeter slopes. The most suitable trees established on the top and flat areas were *Rhus Lancea, Rhus Pendulina, Acacia Karoo* and *Eucalyptus*.



Determination of the best fertilizer for tailings in terms of potassium, nitrogen and phosphate indicated that initial fertilization with 4:3:4 (N:P:K) with on-going N and K supplements.



Irrigation trials in progress.



Determination of the optimum method for irrigation of vegetation indicated that drip irrigation was best resulting in the greatest leaching, diversity and basal cover.

FREE STATE (CONTINUED)



Shaping of the paddocks on the upper surface of the facility during rehabilitation work.



Determination of the optimum species of nitrogen fixers indicated that Lucerne and White or Red Clover were best.



Determination of optimum lime concentrations for a tailings pH of 2-4 indicated that a combination of lime and compost should be applied at a rate of 30t/ha.



Determination of the optimum compost mulch and surface cover with the most suitable carbon: nitrogen ratio indicated an application rate of 10t/ha of compost.

FREE STATE (CONTINUED)



Evaluation of the sustainability of grass and tree species on the slimes dam slopes.



The most successful grasses were Rhodes and Weeping Love.



Evaluation of different rock cladding and vegetation techniques with respect to slope stability, surface run-off and sustainability indicated that layer protection is required between the rock and the tailings.



Evaluation of feasibility of vegetable production of top of tailings facility in tailings material. The successful crops were spinach, radish and cabbage.

FREE STATE

Mineral mined: Gold.

Mining company: Anglo American Corporation of South Africa – Gold Division.

Location: Welkom, Free State, South Africa.

Climate: Summer rains, chilly winters and sunny. MAP: 560mm.

Nature of mine residue: Metallurgical plant slimes.

Area rehabilitated: Western Holdings Slimes Dam.

Rehabilitation objective: Slimes dam closure.

Clearing and topsoil management: Nil.

Rehabilitation earthworks:

- Slope flattening prior to vegetation establishment.
- Removal of all benches on slopes.

Revegetation:

- Establishment of grasses directly into the slimes material.
- Use of pioneer vegetation such as wheat to facilitate establishment of desired and sustainable grasses.
- Irrigation of vegetation during the initial stages.

Timing: Rehabilitation commenced after slimes dam was decommissioned.

Fauna: Installation of perches for predatory birds to control rodents.

Weed and feral animal control: Fences.

Erosion control: Vegetation.

Learning points:

- Improved conditions for vegetation establishment.
- Slopes should be flattened to gradients that can be traversed by mechanical plant required for rehabilitation activities.
- Costs compare favourably with conventional methods. Initially higher due to civil engineering costs but lower vegetation and maintenance costs.
- Flatter slope allows the use of less labour intensive sprinkler irrigation systems.
- No erosion after abnormally high rainfall.
- 18° too steep - 15° ideal.

References: NH Theunissen (personal communication).

FREE STATE (CONTINUED)



View of the slimes dam undergoing slope flattening with the original eroded benches evident on the right hand side of the photograph.



Balanced cut-to-fill slope flattening by dozing from the top of the facility.



Aerial view of the slimes dam showing the closure profile with the perimeter slopes flattened.



View of a section of the slimes dam perimeter having been flattened and vegetation established on the slopes.

IDUAPRIEM

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Southern Ghana, West Africa.

Climate: Tropical, warm and humid. MAP: 2.000mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Tailings facility formed via upstream earthwork raises – 85ha.

Rehabilitation objective: Prevent erosion of tailings facility.

Rehabilitation earthworks: No special earthworks undertaken.

Timing: Rehabilitation started in June 2000.

Erosion control: Vegetation establishment.

Learning points:

- Relative ease of vegetation establishment in amenable climate.
- Value of focussed rehabilitation efforts.

IDUAPRIEM (CONTINUED)



Supernatant pond on old tailings facility. Note the vegetation on the dry basin sections.



Vegetation on the dry basin sections.



View along crest of the tailings impoundment wall. The roadway marks the wall centreline and with the outer wall on the left of the picture. The right hand side is the basin section.



Dense vegetation on the tailings facility basin.

IDUAPRIEM (CONTINUED)



Shallow section of the supernatant pool.



Trial sections of maize and other crops on the tailings facility.



Dense vegetation on the tailings facility basin.

IDUAPRIEM

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Southern Ghana, West Africa.

Climate: Tropical, warm and humid. MAP: 2.000mm.

Nature of mine residue: Waste rock overburden material.

Area rehabilitated: Waste rock dumps – 39ha.

Rehabilitation objective: Stabilise waste dumps.

Rehabilitation earthworks: Shaping of dump outer profile.

Erosion control: Vegetation establishment.

Learning points:

- Relative ease of vegetation establishment in amenable climate.
- Value of focussed rehabilitation efforts.



Dense vegetation established on waste rock dump.



Dense vegetation on waste rock dump.

IDUAPRIEM

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Southern Ghana, West Africa.

Climate: Tropical, warm and humid. MAP: 2.000mm.

Nature of mine residue: Heap leach material.

Area rehabilitated: Heap leach facility.

Rehabilitation objective: Stabilise heap leach facility.

Rehabilitation earthworks: Nil – vegetation established directly upon slopes as originally stacked.

Erosion control: Vegetation.

Learning points:

- Rapid erosion of loosely stacked heap leach material.
- Poor rehabilitation results in cases where the focus has only been on vegetation establishment and not on ensuring the correct storm water management measures are in place first.



Heap leach facility showing significant erosion despite some vegetation establishment measures in the past.

JERRITT CANYON

Mineral mined: Gold.

Mining company: Independence Mining Corporation/AngloGold (Jerritt Canyon) Corp.

Location: North-eastern Nevada.

Climate: MAP: 250-300mm MAE: 1.500mm

Nature of mine residue: Metallurgical plant tailings.

Area to be rehabilitated: Tailings facility.

Rehabilitation objective: Prepare facility for closure whilst maximising depositional capacity via removal of large volumes of excess water from the facility surface.

Rehabilitation earthworks: Nil to date.

Revegetation: Slope vegetation during operational phase.

Animal control: Fences.

Erosion control: Slope vegetation.

Monitoring: Regular monitoring of pool volumes and comparison with target reduction rate.

Other details:

- Water balance aggressively managed via the use of misters and beach irrigation to maximise evaporative losses.
  - Two turbo misters per barge and a large irrigation sprayer.
  - Each barge has a dedicated pump feeding the two turbo misters and one sprayer. The barge is a standard floating platform.
  - The system is run continuously to maximize the evaporation.
  - Designed and built the system in-house.
  - Anti-scalent is added to the influent water due to TDS concentrations.
  - Evaporation efficiencies estimated at 30-40% of throughput.
- Seepage emanating from tailings facility is managed via a comprehensive system of abstraction and injection wells around the facility perimeter. This is necessary because facility is unlined which is unusual in the States.

Learning points:

- Importance of minimising water storage on the tailings facility to limit environmental issues (seepage) and to maximise capacity (reduce the need for expensive raises).
- Generation of hyper-saline process water through evaporation and problems associated with scaling of pipes and the unsuitability of the use of this water in the metallurgical process.
- Difficulty and expense of seepage management during and after tailings facility closure.

JERRITT CANYON (CONTINUED)



August 1999 – view of tailings facility showing the substantial supernatant pool.



August 1999 – View of relatively short beach caused by large pool. Crest of perimeter wall is in the foreground.



August 1999 – high flotation vehicle on beach. Relocation of beach irrigation infrastructure.



August 1999 – Beach irrigation in progress.

JERRITT CANYON (CONTINUED)



August 1999 – Abstraction well at tailings facility toe.



August 1999 – Impoundment wall crest – note the vegetation establishment on the outer face.



August 1999 – Localised seepage causing vegetation die-off.



August 1999 – Outer face of the impoundment wall with vegetation.

JERRITT CANYON (CONTINUED)



December 2000 – View of tailings facility showing reduced supernatant pool.



December 2000 – Crest of impoundment wall.



December 2002 – View of tailings facility showing snow cover.



December 2002 – Crest of the impoundment wall.

JERRITT CANYON (CONTINUED)



Spray evaporation system comprising barge-mounted sprays in the centre of facility, beach irrigation sprays for beach wetting and evaporation and boom-mounted sprayers.



Closer view of barge-mounted sprays.



Boom-mounted sprays at the perimeter were used sporadically as a result of drift and maintenance issues.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: Tropical with moderate temperatures. MAP: 1.500mm MAE: 800mm.

Nature of mine residue: Calcine tailings.

Area rehabilitated: Cycloned underflow impoundment wall of Calcine tailings facility.

Rehabilitation objective: Prevent erosion of outer face of impoundment and prepare tailings facility for ultimate closure.

Rehabilitation earthworks: Profile creation by cyclone deposition and minor shaping by mechanical plant to form benches.

Revegetation: Vegetation of outer face of impoundment wall by seeding directly in tailings material. Grass mats used to prevent erosion during vegetation establishment. Legumes planted for nitrogen cycling. Repairs of eroded sections using grass sprigs.

Timing: As cycloning took place in a downstream manner vegetation establishment has only become possible now that the wall has attained its final elevation. Seeding commenced in 2002 under irrigation.

Nutrient cycling: Legumes.

Weed and feral animal control: Fences.

Erosion control: Benches, half-round channels at toe of benches and vegetation establishment.

Monitoring: Repair work and monitoring continue to date and beyond.

Learning points:

- Relative ease of vegetation establishment in amenable climatic conditions.
- Calcine material is relatively inert because of metallurgical process and therefore supports vegetation growth.
- Cycloned underflow erodes readily because of its uniform grading and must therefore be stabilised soon after deposition.

MORRO VELHO (CONTINUED)



October 2000 - View of the main impoundment wall prior to any rehabilitation. Cyclone deposition in downstream manner precludes revegetation at this stage.



August 2002 - Outer face of impoundment wall with a section having been seeded and under irrigation.



August 2002 - View along bench at seeded section.



August 2002 - View down slope showing irrigation.

MORRO VELHO (CONTINUED)



August 2002 - View of the impoundment wall at the start of rehabilitation efforts.



August 2002 - Close-up of impoundment wall at the start of rehabilitation efforts.



July 2003 - View along benches showing neat profile and successful vegetation establishment.



July 2003 - View of impoundment wall with rehabilitation efforts evident.

MORRO VELHO (CONTINUED)



May 2004 - View along crest of the impoundment wall showing good vegetation growth. Upstream face not vegetated.



May 2004 - Close-up of section of face showing vegetation.



May 2004 - View of toe of bench showing vegetation and storm water collection channel at toe.



May 2004 - View along bench showing vegetation.

MORRO VELHO (CONTINUED)



May 2004 - View down face of impoundment wall showing repair of eroded section.



May 2004 - View along bench showing vegetated profile.



May 2004 - View of outer face of impoundment wall showing results of vegetation establishment programme.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: MAP: 1.500mm MAE: 800mm.

Area rehabilitated: Natural slopes surrounding and upstream of tailings facilities.

Rehabilitation objective: Prevent erosion of the natural slopes and limiting the transport of this material to the basins of the tailings facilities to maximise tailings disposal capacity and prepare for ultimate closure.

Rehabilitation earthworks:

- Gabions formed at the base of the eroded sections to hold back eroded material.
- The gabions are the raised as they are silted up.
- Earthworks to repair eroded sections.

Revegetation: Trees are planted in the surrounding slopes to stabilise the slopes.

Erosion control: Vegetation and drainage control measures.

Monitoring: Repairs undertaken and gabions raised as necessary.

Learning points:

- Any disturbance to the natural slopes, e.g. formation of tracks, roads or borrow-pits, quickly results in severe erosion.
- Severe problem that requires concerted efforts and long term commitment to rectify.
  - Could compromise the integrity of the downstream tailings facilities if neglected.

MORRO VELHO (CONTINUED)



November 2001 – One of the many eroded sections prior to the initiation of slope stabilisation measures. This erosion is generally caused by deforestation and disturbance such as roads, tracks or borrow areas.



August 2002 – Deep erosion upstream of the Cocuruto tailings facility prior to treatment. The material from this and other sections necessitated the raising of the impoundment wall to ensure adequate freeboard.



August 2002 – The same section but with a gabion at the mouth of the eroded area. This gabion has successfully stopped material from leaving the section and from entering the tailings facility. The gabion has subsequently been raised and saplings have been planted on the slopes.



July 2003 – Another section after earthworks to repair erosion. These areas will be planted with trees to stabilise the slopes.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: MAP: 1.500mm MAE: 800mm.

Area rehabilitated: Pit slope rehabilitation.

Rehabilitation objective: Stabilise pit slopes.

Rehabilitation earthworks: Benches and berms formed during mining operations – no further rehabilitation earthworks post mining.

Revegetation: Grass establishment via the use of grass mats fixed to soil and rock slopes.

Erosion control: Vegetation establishment on benches and berms.

Learning points:

- Innovative use of grass mats for vegetation establishment – potential application elsewhere and on tailings facility slopes.
- Use of local sub-contractors to assist with rehabilitation efforts.
- Relative ease of vegetation establishment in amenable climatic conditions.

MORRO VELHO (CONTINUED)



Grass mats used to stabilise high wall faces. Climbers, with safety gear, abseil down the high wall and secure the mats to the face.



Results after 2-5 years of growth.



Construction of the grass mats – nylon lattice net hand-tied to support the interwoven grass.

MORRO VELHO (CONTINUED)



Harvested grass.



Heavy nylon tape backbone with lighter nylon tape support.



Rolls of grass mats. Fertiliser and seed are included in the grass matrix.

MORRO VELHO (CONTINUED)



On-site manufacture of wooden pegs.



Wooden pegs used to secure pegs to high wall face.



Grass mats on a sandy high wall face. Surprisingly good results are obtained on rocky faces.

MORRO VELHO (CONTINUED)



Results from 2-5 years of growth.



A case for local innovation, experimentation and application.

NAVACHAB

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Karibib, Central Namibia.

Climate: Arid to semi-arid. Hot days and cool nights. MAP: 200mm MAE: 3.000mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Cycloned upstream tailings facility.

Rehabilitation objective: Preparation of tailings facility for final closure during operation minimising the amount of work required after decommissioning.

Clearing and topsoil management: Suitable soils stripped from mining areas and used for rehabilitation.

Rehabilitation earthworks:

- Cladding of outer face of cycloned impoundment walls with waste overburden material by end-tipping during the operational life of the tailings facility. This was possible as the walls were raised using the upstream method.
- Topsoil material end-tipped over the waste rock to promote vegetation growth.
- Benches profile to shed storm water to ends.
- Side channels collect and discharge storm water from benches to toe. These channels have been stone-pitched.
- The upper surface of the facility was shaped by slurry deposition to achieve a profile that would shed water to a natural saddle where a closure spillway will be created through the natural rock.

Revegetation:

- Topsoil contains seeds so vegetation establishment takes place naturally.
- Saplings have recently been planted in pockets close to the outer edges of benches.

Timing:

- Rehabilitation work has occurred throughout the operational life.
- The upper surface is to be capped now that the facility has attained its final capacity.

Weed and feral animal control: Fences.

Erosion control: Rock cladding, benches and down-chutes.

Learning points:

- Commence rehabilitation activities during operational phase wherever possible.
- Importance of planning deposition to minimise the amount and cost of closure.
- Difficulties of protecting slopes where vegetation establishment is not a viable solution to slope stabilisation.

NAVACHAB (CONTINUED)



Dust generation from tailings facility soon after decommissioning. The crest of the cycloned impoundment walls is highly susceptible to wind erosion. Natural vegetation during the wet season.



Unclad slope of impoundment wall prior to rock cladding.



Erosion from an intense storm soon after decommissioning. The access ramps are especially vulnerable.



Erosion from one bench to the next despite waste rock cladding. This erosion was initiated by inadequate gradients on the benches.

NAVACHAB (CONTINUED)



View along a bench on a rock-clad section of the impoundment wall. Note the transport of tailings underflow material from beneath the rock cladding onto the bench. Waste rock material has been tipped along the outer edge of the bench for cladding purposes.



Close-up of the bottom edge of the waste rock clad slope where it meets the horizontal bench. Note the tailings underflow material washed from beneath the cladding.



View looking down slope showing the tailings underflow material washed out.



View of a stone-pitched side-channel at the point where the bench connects.

NAVACHAB (CONTINUED)



Sapling planted close to the outer edge of the bench. Note the 'rat-hole' erosion emanating from the excavation for the tree.



Unclad section of an impoundment wall. Note the wind-blown deposition of underflow material in places.



View of the upper surface of the tailings facility.



Another view of the tailings facility basin having been shaped to discharge storm water to the point at which a closure spillway is to be formed through the natural *in situ* material.

NAVACHAB (CONTINUED)



View of a portion of the tailings facility basin and an impoundment wall.



Toe of an unclad section of the impoundment wall. Note the water erosion of underflow material from a single intense storm.



Close-up of tailings underflow material near the impoundment wall crest showing the effects of wind erosion.



Wind erosion in progress at the impoundment wall crest.

OBUASI

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Ghana, West Africa.

Climate: Tropical, warm and humid. MAP: 1.400mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Tailings facility during the operational phase.

Rehabilitation objective: Minimise erosion during the operational phase.

Clearing and topsoil management: Nil to date.

Rehabilitation earthworks: Nil to date.

Timing: During operational phase.

Weed and feral animal control: Nil.

Learning points:

- Importance of ensuring that storm water drainage details and earthworks have been properly conducted prior to commencing vegetation establishment.
- Rapid deterioration of tailings facilities after decommissioning where rehabilitation works have not been successfully concluded.

OBUASI (CONTINUED)



Sansu tailings facility – some revegetation of outer slopes during operational life.



Sansu tailings facility – progressive rehabilitation of outer slopes.



Sansu tailings facility – seepage from toe of revegetated impoundment wall.



East Kokoteasua tailings facility – remnant pool two years after decommissioning.

OBUASI (CONTINUED)



East Kokoteasua tailings facility – severe erosion of cycloned upstream wall two years after cessation of deposition.



East Kokoteasua tailings facility – erosion of benches on cycloned main impoundment wall. Note the defunct drainage collection channel.



East Kokoteasua tailings facility – residential area immediately downstream of toe and expanding even closer.



Arsenic impacted area – damage from old roaster stack emissions.

SADIOLA HILL

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd/Iamgold.

Location: North-western Mail, West Africa.

Climate: Subtropical to arid. Hot and dry June to November. Cooler and dry November to February. Influenced by proximity to Sahara Desert (200km away). Harmattan arid trade wind. MAP: 800mm MAE: 2.900mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Vegetation and rock-cladding establishment trials on cycloned underflow tailings impoundment wall and compacted laterite starter wall.

Rehabilitation objective: Establish methodology for slope rehabilitation and vegetation establishment within tailings.

Clearing and topsoil management: Some areas of site stripped of topsoil for future rehabilitation use.

Rehabilitation earthworks: Benches.

Revegetation: Grass establishment on slopes.

Timing: During the operational phase.

Weed and feral animal control: Fences.

Erosion control: Vegetation establishment.

Learning points:

- Underflow material is highly susceptible to erosion and vegetation does not adequately bind this material.
- Difficulties of working in extremely hot (48°C) environment.
- Importance of creating the correct geometry for storm water control prior to vegetation establishment.

SADIOLA HILL (CONTINUED)



July 2002 – Compacted laterite starter wall seeding.



July 2002 – Starter wall seeding.



Subsequent erosion of section of the starter wall as a result of intensive rain.



Erosion down the face of the starter wall. Note the timber used to retain mulch during germination.

SADIOLA HILL (CONTINUED)



View down the starter wall face at an eroded and subsequently repaired section. Note the repeated erosion.



Dumping of topsoil/growth medium on bench for vegetation establishment.



Access difficulties during topsoil placement activities on narrow benches.



Wet season 2003 – View along the main impoundment wall showing the vegetation establishment on the cycloned underflow material.

SADIOLA HILL (CONTINUED)



Dry season 2004 – The same section a year later and during the dry season.



Wet season 2003 – View along the main impoundment wall after rains.



Dry season 2004 – A reverse view of the same section but during the dry season.



An eroded section of the cycloned material slope.

SERRA GRANDE

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd/TVX.

Location: Crixas, Goais State, Brazil.

Climate: Sub-tropical with high temperatures. MAP: 1.600mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Outer face of cycloned upstream impoundment wall.

Rehabilitation objective: Minimise erosion and prepare the facility for ultimate closure.

Rehabilitation earthworks:

- Benches formed at intervals up impoundment wall.
- Drainage of benches to side-channel down-chutes.
- Cladding of slopes with waste rock material.

Revegetation: Vegetation establishment within the waste rock cladding material.

Timing: During the tailings facility operational phase.

Erosion control: Benches and waste rock cladding.

Other details: Tailings material is cycloned close to the impoundment wall and stockpiled for use as underground backfill material. This material is excavated and then transported underground for stabilisation of workings.

Learning points:

- Value of coarse tailings fraction for underground stabilisation purposes.
- Ease of vegetation establishment in amenable climate.
- Waste rock material is relatively well graded and is therefore not prone to erosion.
- Importance of good storm water management details.
- Importance of ensuring good vegetation cover at the crest of the impoundment wall to minimise wind erosion and dust generation.

SERRA GRANDE (CONTINUED)



October 2000 – View along bench of main impoundment wall. Note the waste rock cladding with some vegetation growth.



October 2000 – View down-slope with the side-channel evident to the left of the photograph.



October 2000 – Unclad cycloned material showing some erosion onto the bench.



November 2001 – View down-slope a year later.

SERRA GRANDE (CONTINUED)



November 2001 – View along bench showing some ponding of storm water after rains.



July 2002 – View along bench – note the good freeboard provided at the outer limit of the bench.



July 2003 – View along the crest of the impoundment wall – note the absence of vegetation.



May 2004 – View along the outer face – note the good vegetation establishment.

SERRA GRANDE (CONTINUED)



May 2004 – View along bench showing vegetation.



May 2004 – View of upper surface of tailings facility that will require capping at the end of the useful life of the facility.



May 2004 – Vegetation established right to the crest of the main impoundment wall to prevent dust generation. Some irrigation of the beach in this zone was conducted to further suppress dust.

SIGUIRI

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Siguiri, Eastern Guinea, West Africa.

Climate: Subtropical to arid. Hot and dry June to November. Cooler and dry November to February. Influenced by proximity to Sahara Desert. Harmattan arid trade wind. MAP: 800mm MAE: 2.900mm.

Nature of mine residue: Waste overburden comprising soils and rock.

Area rehabilitated: Waste overburden dumps and mined-out areas.

Rehabilitation objective: Stabilise dumps preventing erosion.

Rehabilitation earthworks:

- Reshaping of disturbed areas.

Revegetation: Planting of saplings.

Erosion control: Slope flattening and reshaping and revegetation.



Waste overburden dump area reshaped and prepared for rehabilitation.



Saplings planted on reshaped area.



Vegetation planted on steep faces to control erosion.

TASMANIAN EXAMPLE

Mineral mined: Gold.

Location: Central Tasmania, Australia.

Climate: Mild, temperate maritime. MAP: 2.400mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Tailings facility.

Rehabilitation objective: Close tailings facility whilst accommodating safe discharge of excess storm water given the high rainfall experienced in this region.

Learning points:

- Storm water management issues and solutions in high rainfall area.
- The formation of a natural environment in keeping with surroundings.



Lake area formed on decommissioned tailings facility surface near overflow spillway.



Basin area of original tailings facility during re-shaping and topsoil application operations. The closure objective was to create a stream that would meander across the facility surface.



View of the stream that traverses the surface of the original tailings facility.

WEST WITS

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd – South Africa Region.

Location: West Witwatersrand, South Africa.

Climate: Highveldt. MAP: 700mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant slimes.

Area rehabilitated: Slimes dams.

Rehabilitation objective: Sustainable vegetation of slimes dams.

- Experimental implementation and assessment of land-use plans designed to facilitate sustainable pollution containment and potentially mine closure.
- Experimental reduction of slimes dam slopes and indigenous vegetation approach.
- Experimental woodlands and plantations on the tops and around the base of gold slimes dams and over polluted streams and aquifers in the goldfields.

Revegetation: Trial blocks using exotics and indigenous trees.

Learning points:

- Pasture grassing of steep slimes dam slopes is not ecologically or economically sustainable.
- Although pasture grassing of steep slopes contributes to temporary dust control, the grass requires intensive irrigation and fertilisation for establishment, requires continual maintenance, lacks persistence, regenerates poorly (by seed) and contributes little to erosion control.
- The dominant naturally-colonising & persistent vegetation of gold slimes dams is indigenous, perennial, woody and semi-woody.
- 'Naturally-selected' plants and micro-organisms can grow extremely well in slimes,
- Some trees and other plants which grow well in slimes are commercially valuable and could form the basis of rehabilitation products industries on the goldfields.
- The persistence of any vegetation and fostering of ecosystem processes in slimes is significantly improved by :
    - Reduction of slopes.
    - Introduction of organic matter (compost, litter) & physical & chemical heterogeneity to slopes (i.e. textural soil classes, gravels, textural vegetation).
    - Introduction of tolerant micro-organisms (mycorrhizal fungi & nitrogen-fixing bacteria).
    - Use of tolerant land-races of plants.

References: Weiersbye (2002a and 2002b).

WEST WITS

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd – South Africa Region.

Location: West Witwatersrand, South Africa.

Climate: Highveldt. MAP: 700mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant slimes.

Area rehabilitated: Areas downstream of slimes dams to prevent potential pollution.

Rehabilitation objective: The use of strategic tree plantations to contain seepage and ground water pollution and experimental woodlands and plantations on the tops and around the base of gold slimes dams and over polluted streams and aquifers in the goldfields.

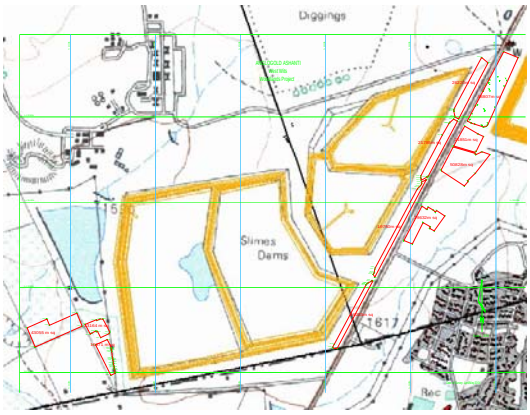
Revegetation: Trial blocks using exotics and indigenous trees.

Learning points:

- There exist a range of indigenous and some exotic woody species (forbs, shrubs and trees) were extremely tolerant of growth in acid and saline slimes, and could maintain productivity and viable seed production equivalent to conspecifics in unpolluted veldt.
- Value of strategic plans developed in conjunction with regulators and that encompasses areas greater than a single owner's mine site.

References: Weiersbye (2002a and 2002b).

CASE STUDY – WEST WITS (CONTINUED)



Map of the slimes dams with the woodlands trial sections located in blocks around the perimeter. The blocks were located after hydro-geological modelling.



Aerial photograph of the slimes dams.



Woodlands blocks in between two slimes dams.



Woodland blocks downstream of the slimes dam.

CASE STUDY – WEST WITS (CONTINUED)



Weed control during early stages of woodlands establishment.



Indigenous plantation adjacent to slimes dam.



View along sapling rows in plantation.



Saplings in plantation.

APPENDIX – CASE STUDIES

(ENCAPSULATION CASE)

BIG SPRINGS

Mineral mined: Gold.

Mining company: Independence Mining Corporation/AngloGold (Jerritt Canyon) Corp.

Location: North-eastern Nevada.

Climate: MAP: 150-200mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: 20ha sub-aerial tailings facility with initial low-permeability soil liner with full drainage blanket and zoned, earth fill embankment.

Rehabilitation objective: Reclamation and mine closure to minimise infiltration.

Clearing and topsoil management: Vegetation and topsoil stripped prior to initial tailings deposition.

Rehabilitation earthworks:

- Re-shaping of tailings facility basin to create a mounded surface using a combination of tailings and fill to establish run-off.
- Cover design alternatives included: a) an evaporative cover comprising 915mm of plant growth media; b) low permeability cover of 450-600mm plant growth media plus 300mm of low permeability material underneath.

Revegetation: 915mm thick vegetated soil evapo-transpiration cover selected on the basis of water-balance modelling. Planting to promote revegetation and maximise evapo-transpiration.

Timing:

- Tailings facility used for deposition from 1988-1994.
- Tailings facility used for site water management and continued gold recovery until reclamation activities in summer 2000.

Weed and feral animal control: Fences.

Erosion control: Gentle, vegetated slopes.

Learning points:

- Sub-aerial deposition provides a cost-effective method by increasing tailings density.
- Sub-aerial deposition results in tailings mass amenable to grading and reclamation.
- Value of field tests.
- Balanced cut-to-fill to minimise cost of earthworks.
- Importance of allowing for settlements of tailings in closure design.

References:

- Ulrich *et al* (2000).
- Reisinger *et al* (2001).

BIG SPRINGS (CONTINUED)



Big Springs tailings facility in December 2000.



Crest of impoundment wall of tailings facility shortly after reclamation.



Outer slope of tailings facility.



Shaded north slope of tailings facility – note snow cover.

CERRO VANGUARDIA

Mineral mined: Gold and silver.

Mining company: AngloGold Ashanti Ltd.

Location: Patagonia, Argentina.

Climate: Arid, cold and wind-swept. MAP: 100mm MAE: 1.800mm.

Nature of mine residue: Gold metallurgical plant tailings.

Area rehabilitated: Nil to date.

Learning points:

- Erosion prevention in a climate that makes vegetation establishment difficult.
- Potential use of Patagonian gravel for tailings facility rehabilitation.



Impoundment wall formed from Patagonian gravels. Wall includes HDPE liner with leak detection system. Native vegetation in foreground.



Impoundment wall with slurry line and slurry discharge points in distance.



Tailings material showing effects of cold winds.

COAL DISCARDS DUMPS – KWAZULU NATAL

Mineral mined: Coal.

Location: Northern Kwazulu Natal, South Africa.

Climate: Sub-tropical. MAP: 840mm.

Nature of mine residue: Coal washing plant discards and slimes.

Area rehabilitated: Colliery discards and slimes dumps.

Erosion control: Whale-back shedding surface or terraced slopes with down-chutes.

Rehabilitation philosophy: The adopted rehabilitation philosophy depended upon the nature of the material, existing topography, rainfall, surrounding environment, availability of natural resources (topsoil, water, organics, *et cetera*), and, importantly, cost.

Other details: The approach involved:

- Removal of existing infrastructure and recovery of salvageable material.
- Engineering works: reshape to the desired profile for aesthetics, stability, erosion and storm water control (computerised modelling of different options to minimise quantity of material moved).
- Selection of cover configuration and materials (ameliorate existing material, imported topsoil layer).
- Vegetation (dry-lands or irrigated, use of a mother crop to stabilise slopes as soon as possible, introduction/utilisation of indigenous species).

Learning points:

- Each facility has its own unique circumstances.
- Do not cut corners to save money in the short term.
- The importance of effective engineering works.
- Avoid complacency and cater for the unexpected.
- Avoid recipe solutions.
- The importance of ongoing maintenance.
- Vegetation species varied according to slope angle and length.
- Problems with animals grazing as soon as vegetation started to grow.
- Liability legacies accrued to new land owner.

References:

D. Cameron (personal communication).

COAL DISCARDS DUMPS - KWAZULU NATAL (CONTINUED)



Colliery discards dump A before rehabilitation. Problems:

- Long steep eroded slopes.
- Areas of combustion.
- Coal washing plant & infrastructure.
- Polluted run-off and seepage.



Dump A during rehabilitation works:

- Burning areas exposed and covered with compacted material.
- Waste and rubble buried within the dump.
- Formal storm water run-off control measures.
- Topsoil (150mm) and vegetated.



Dump A after rehabilitation:

- Burning extinguished.
- Erosion limited.



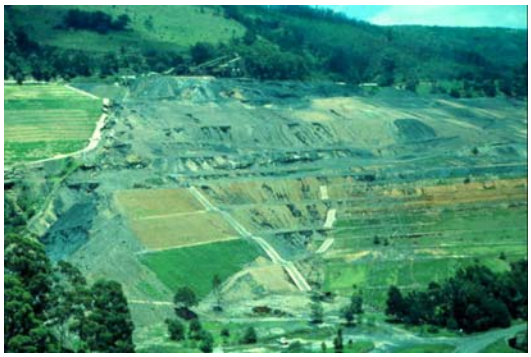
Dump A after rehabilitation in dry season.

COAL DISCARDS DUMPS – KWAZULU NATAL (CONTINUED)



Colliery discards dumps B & C before rehabilitation:

- Long steep slopes heavily eroded.
- Areas of combustion.
- Mine plant and sundry waste.
- Polluted run-off and seepage.



Dumps B & C during rehabilitation:

- Most of the cost of rehabilitation paid for from saleable coal recovered in the dumps.



Dump B during rehabilitation works – severe erosion at end of down-chutes after heavy rains.



Dump B during rehabilitation works – severe erosion at end of down-chutes after heavy rains.

COAL DISCARDS DUMPS - KWAZULU NATAL (CONTINUED)



Dumps B & C after rehabilitation:

- Burning extinguished.
- Erosion limited.



Colliery discards dump D before rehabilitation:

- Semi-terraced side slopes.
- Areas of combustion.
- Mine and domestic waste.
- Polluted water run-off.



Dump D during rehabilitation.



Dump D after rehabilitation:

- Terraces reformed.
- Formal run-off control.
- Burning exposed and covered with compacted material.
- Topsoil and vegetation.

COAL DISCARDS DUMPS - KWAZULU NATAL (CONTINUED)



Colliery discards dump E before rehabilitation:

- Areas of combustion.
- Erosion.
- Polluted run-off
- Polluted seepage.
- Close to water-course.



Dump E during rehabilitation works:

- Reshaped to whale-back profile.
- Burning areas exposed and capped.
- Discards moved away from water-course flood line.
- Compacted subsoil and topsoil layers.
- Vegetated.



Dump E after rehabilitation.

COAL DISCARDS DUMP – WITBANK

Mineral mined: Coal.

Location: Witbank, Mpumalanga, South Africa.

Climate: Highveldt. MAP: 700mm MAE: 1.500mm.

Nature of mine residue: Coal washing plant discards and slimes.

Area rehabilitated: Colliery discards and slimes dumps – 111ha.

Rehabilitation objective: Reduce air pollution (poor visibility and bad smell), improve water quality, and rehabilitation of the valley and burning discards dump.

Timing: 1989 – 2000 in three phases.

Erosion control: Whale-back shedding surface with vegetated slopes.

Other details:

- Total project cost was R16,5M (2000).
- Maintenance costs are R90.000/year.

Learning points:

- Excellent example of undertaking closure properly with a successful end-result.
- Re-shaping and closure of a burning discards dump is dangerous work that must be carefully managed with the correct equipment and safe working practices.
- Community involvement (game camp, bailed animal feed from valley rehabilitation and fertilizer application, fire-break establishment and mowing of the grass).

References: Mining Weekly (http://www.mining weekly.co.za/min/features/environmental)



Discards dump prior to rehabilitation activities. Large portions of the dump were burring resulting in poor visibility in the winter and bad smell. Other problems included water pollution and the presence of dangerous ground.



A view of one of the faces of the dump soon after reshaping and vegetation establishment. Note the bailed grass cut from the slopes.

ERGO DAGGAFONTEIN

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Springs near Johannesburg, South Africa.

Climate: Highveldt. MAP: 600-700mm MAE: 1.500mm.

Nature of mine residue: Reprocessed metallurgical plant tailings hydraulically reclaimed from numerous slimes dams east of Johannesburg.

Area rehabilitated: Plan area of tailings facility of 435ha.

Rehabilitation objective: Reclamation and mine closure.

Clearing and topsoil management: No topsoil stripping of footprint prior to commissioning.

Rehabilitation earthworks:

- Re-profiled outer slopes to 18°-20° slope & 5m wide benches at 13m vertical spacing.
- Application of 300mm thick layer of 60% waste rock and 40% topsoil.
- Upper surface to remain concave with water draining to pool at the centre.

Revegetation: Providing vegetation, including wood lots, on the upper surface of the facility. The slope cover comprises: *Eragrostis Curvula* (Weeping love grass), *Chloris Gvana* (Rhodes grass), *Cynodon Dactylon*, 'Kweek'), *Panicum Maximum* (Blue Buffalo grass), and *Digitaria Eriantra* (Smuts finger grass).

Timing: Slimes deposition ceased in December 2001, active water management to 2005, implementation to end 2006, active maintenance to 2014 and closure thereafter.

Erosion control: Vegetated, armoured topsoil layer and concrete-lined down-chutes.

Learning points:

- Gold recovered from large-scale slimes dam reprocessing.
- Importance of slope erosion control and monitoring.
- Substantial reduction in environmental liability by consolidation of numerous slimes dams into two mega-facilities.
- Earlier efforts directed at rehabilitation controlled the erosion of the slopes during operation but were not adequate for final closure.
- A number of different types of down-chute structures were constructed during operation to determine the optimum design and construction method.
- Balanced cut-to-fill to minimise cost of earthworks during slope re-profiling.
- Benefits of introducing a well-graded capping layer, i.e. waste rock and topsoil mix.
- Difficulties of locating adequate quantities of topsoil available for rehabilitation.
- Importance of working systematically in accordance with details and specification.

References: Golder Associates (2003b and 2003c) and Swart (2004).

ERGO DAGGAFONTEIN (CONTINUED)



Aerial view of the Daggafontein tailings facility – note the large supernatant pool, the proximity to a natural water-course and the partially vegetated outer slopes.



Tailings facility prior to rehabilitation efforts after plant decommissioning.



View of the tailings facility slopes with the original vegetation establishment work evident on the outer slopes. Note the disturbance caused by subsequent re-grading of the berms and also the down-chutes at intervals along the face.



Close-up view of the vegetation on the outer face of the tailings facility. The method originally adopted was to apply a thin layer of topsoil down the face and to let this self-seed.

ERGO DAGGAFONTEIN (CONTINUED)



2001 – Erosion at external corner of tailings facility (Windy Corner).



View of the face of the tailings facility from the toe looking upwards. Note the erosion channels and the absence of vegetation close to the toe.



Rehabilitation trials with reshaping in progress.



Reshaping and armouring of external corner (Windy Corner).

ERGO DAGGAFONTEIN (CONTINUED)



End-tipping of topsoil/rock mix on prepared slope.



Spreading of cover material to the required thickness by dozer.



Installation of storm water down-chutes.



Reshaping and cladding activities in progress.

ERGO DAGGAFONTEIN (CONTINUED)



Reshaping and cladding activities in progress.



Shaped, armoured and vegetated slopes.



Section of slope with vegetation established.

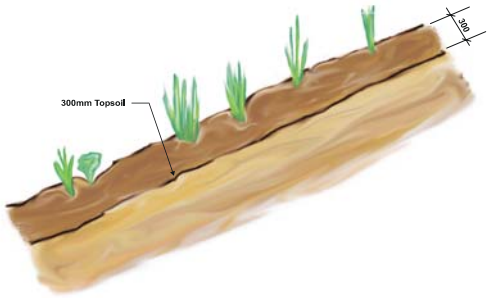


Vegetation establishment trials.

ERGO DAGGAFONTEIN (CONTINUED)

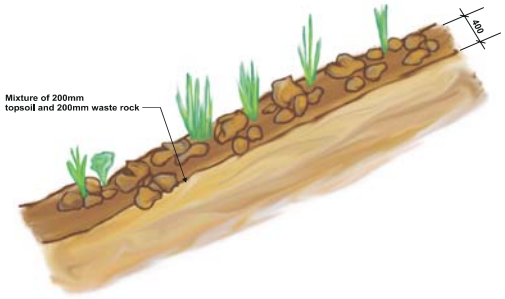


Final closure works commenced after plant decommissioning conducted in a systematic manner, commencing with re-profiling and shaping of the face in accordance with design details and specifications, and application of topsoil and armouring. Storm water is led off the berms via down-chutes. Note original, un-profiled face in background.



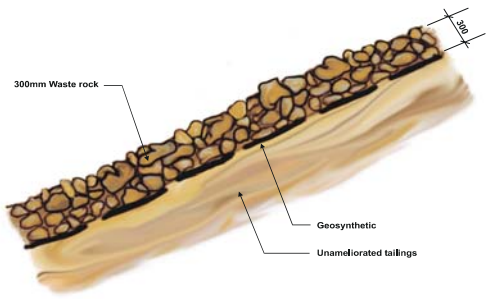
Daggafontein Closure : Surface stabilisation Option 1: Topsoil

Option 1: Surface Stabilisation with topsoil.



Daggafontein Closure : Surface stabilisation OptionS 2 & 3 :
Topsoil and armouring

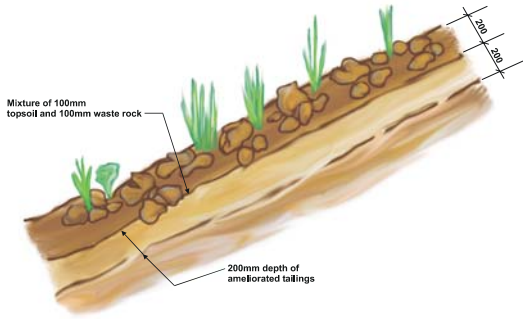
Option 2: Surface stabilisation with topsoil and armouring. This option was selected as it was shown to be the most cost-effective in the long term.



Daggafontein Closure : Surface stabilisation Option 4 : Waste rock cladding

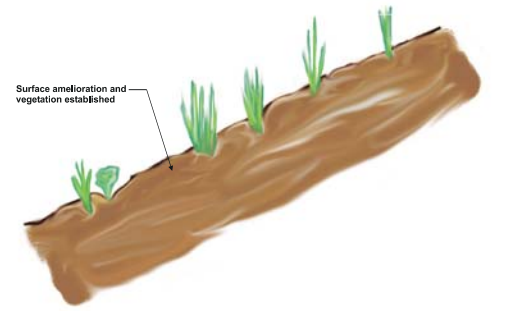
Option 3: Surface stabilisation with waste rock cladding.

ERGO DAGGAFONTEIN (CONTINUED)



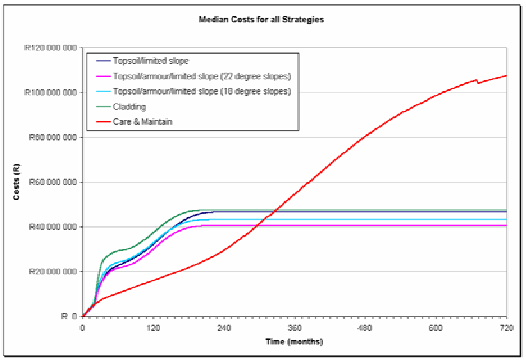
Daggafontein Closure : Optimised surface stabilisation Option 5 : Topsoil, armouring and amelioration

Option 4: Surface stabilisation with topsoil, armouring and amelioration.



Daggafontein Closure : Surface stabilisation Option 6 : Amelioration and vegetation

Option 5: Surface stabilisation with amelioration and vegetation.



- Care and maintenance was shown to be the least costly option in the short term.
- Care and maintenance was shown to be the most costly option in long term.
- Slope modification with armouring was shown to be the best strategy.



Slope erosion monitoring point – an important part of demonstrating success.

GEITA

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: North-western Tanzania.

Climate: Equatorial modified by highland plateau. MAP: 1.000mm MAE: 1.900mm.

Nature of mine residue: Metallurgical plant tailings.

Rehabilitation objective: Minimise seepage from tailings facility via the incorporation of under-drainage system.

Timing: Provision of under-drains prior to tailings deposition.

Learning points:

- Pro-active seepage prevention measures.



View of tailings facility basin during commissioning showing the contact zone between the pool and the base. Note the under-drains laid out in a herringbone pattern.



View along the under-drains prior to inundation by tailings.



View along an under-drain with the impoundment wall in the distance.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: Tropical with moderate temperatures. MAP: 1.500mm MAE: 800mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Compacted earth impoundment wall to Cocuruto tailings facility.

Rehabilitation objective: Prevent erosion of the outer face of the impoundment wall and to prepare for ultimate closure.

Rehabilitation earthworks: Bench and central down-chute formation.

Revegetation: Grasses planted on outer face. Grass is cut annually to facilitate inspection during the operation of the facility.

Weed and feral animal control: Fences.

Erosion control: Vegetation, benches, concrete toe channels and down-chutes.

Monitoring: Minor repairs undertaken as required.

Other details: Extensive erosion of the natural slopes upstream of the Cocuruto impoundment resulted in the siltation of the basin and the need to raise the wall to maintain adequate facility.

Learning points:

- Relative ease of vegetation establishment in amenable climatic conditions.
- Need to cut vegetation during operational life to facilitate inspection.
- Grass establishment during operational life significantly reduced maintenance.
- Importance of good storm water management engineering details.
- Compacted earth fill used to form impoundment wall is much more resistant to erosion that the cycloned underflow material used to form the nearby Calcine tailings facility.
- Face erosion is not a problem despite steep profile because of good vegetation cover and storm water drainage.
- Closure of the tailings impoundment is not possible until the natural slopes upstream have been stabilised.

MORRO VELHO (CONTINUED)



August 2002 - View down the outer face showing the regular geometry, bench drainage, central down-chute and good grass cover. Not the use of steps in the down-chute to dissipate energy.



August 2002 - Outer face showing grass coverage.



July 2003 - Outer face at central down-chute.



May 2004 - Siltation of basin from surrounding slope erosion necessitated additional wall raise and concerted efforts to stabilise natural slopes. External drainage blanket applied to a section of the face.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: Tropical with moderate temperatures. MAP: 1.500mm MAE: 800mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Compacted earth impoundment wall to Rapaunha tailings facility.

Rehabilitation objective: Prevent erosion of the outer face of the impoundment wall and to prepare for ultimate closure.

Rehabilitation earthworks: Bench formation.

Revegetation: Grasses planted on outer face. Grass is cut annually to facilitate inspection during the operation of the facility.

Erosion control: Vegetation, benches and concrete toe channels.

Monitoring: Minor repairs undertaken as required.

Other details: Removal of excess water from facility basin after improvements to water management has resulted in a large exposed beach area that invites recreational use and could result in dust generation.

Learning points:

- Relative ease of vegetation establishment in amenable climatic conditions.
- Need to cut vegetation during operational life to facilitate inspection.
- Grass establishment during operational life significantly reduced maintenance.
- Importance of good storm water management engineering details.
- Compacted earth fill used to form impoundment wall is much more resistant to erosion that the cycloned underflow material used to form the nearby Calcine tailings facility.
- Face erosion is not a problem despite steep profile because of good vegetation cover and storm water drainage.
- Alleviation of one problem often causes others.
- Trespassing can be difficult to control.
- Proximity of tailings facility to human habitation necessitates a strong emphasis on social issues and stakeholder participation.

MORRO VELHO (CONTINUED)



November 2001 - View of the outer face of the impoundment wall. Note the benches and grass-cover slopes.



August 2002 - View of the outer face after cutting of the grass.



July 2003 - Removal of excess water from the tailings facility basin has resulting in a large area that causes new problems. Note the erosion channels on the dry beach sections.



May 2004 - View along the impoundment wall crest showing clearing and earthworks for the next raise.

NORTH AMERICAN EXAMPLE A

Mineral mined: Gold.

Location: Nevada, USA.

Climate: MAP: 150-200mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant tailings.

Rehabilitation objective: No contamination of the ground water from the tailings facility during operation and after closure.

Rehabilitation measures: Fully lined tailings facility – liner installed over complete footprint of tailings facility prior to commissioning.

Other details: Other options being evaluated include use of:

- A portion of the tailings stream for backfill using paste technology.
- High compression thickeners or deep thickeners to improve densities delivered to the tailings impoundment.
- Wick drains to speed up tailings consolidation and drainage.
- Partial backfilling of the pit with tailings and/or waste rock.
- Co-disposal options related to tailings and waste rock.

Learning points:

- USA approach is to apply highest available standards to facilitate permitting process.
- Initial capital costs are high (up to U$100M spent on tailings facility during the construction and operation phase) but long-term liabilities are substantially reduced.



Liners beneath pipes along entire slurry delivery line route, burst detection systems and cyanide detoxification.



Fully lined tailings facility.

NORTH AMERICAN EXAMPLE B

Mineral mined: Gold.

Location: Nevada, USA.

Climate: MAP: 150-200mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant tailings.

Rehabilitation objective: No contamination of the ground water from the tailings facility during operation and after closure.

Rehabilitation measures: Fully lined tailings facility – liner installed over complete footprint of tailings facility prior to commissioning.

Learning points:

- North American approach is to apply highest available standards to facilitate the permitting process.
- Initial capital costs are high but long-term liabilities are substantially reduced.



View of the tailings facility – note the liner up the sinner face of the impoundment wall.



View over the basin of the tailings facility showing the deposition points around the perimeter.

ROBINSON

Mineral mined: Copper.

Mining company: Kennecott Minerals Company.

Location: McGill, Nevada, USA.

Climate: MAP: 150-200mm MAE: 1.500mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: 1.800ha of tailings facility.

Rehabilitation objective: Return the tailings facility surface to pasture for livestock grazing and provide a habitat for abundant wildlife.

Timing: 1993 onwards.

Fauna: Abundant wildlife and livestock.

Learning points:

- Holistic management principles and practice.

References:

http://www.mii.org/nevada/nevada.html



Tailings area before reclamation



Pasture after reclamation



Cattle grazing on reclaimed tailings surface

APPENDIX – CASE STUDIES

(DETOXIFICATION CASE)

MANTOS DE ORO – LA COIPA

Mineral mined: Gold and silver.

Mining company: Placer Dome/TVX Normandy Americas.

Location: Copiapó, Northern Chile.

Climate: High altitude desert (3.900mASL). Very arid. MAP: 15-300mm MAE: 1.900mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Disused open pit.

Rehabilitation objective: Backfill disused open pit.

Other details:

- Novel 'dry' tailings and water management system.
- Mercury management receives special attention.

Learning points:

- Use of filter cake to rehabilitate disused open pit.
- Importance of water conservation in arid areas.
- One of lowest unit fresh water consumption rates in the industry.

References:

http://www.mdo.cl

http://www.placerdome.com



'Dry' stacking of filter cake within disused open pit for rehabilitation and water conservation purposes.

MORRO VELHO

Mineral mined: Gold.

Mining company: AngloGold Ashanti (South America) Ltd.

Location: Nova Lima, Minas Gerais, Brazil.

Climate: Tropical with moderate temperatures. MAP: 1.500mm MAE: 800mm.

Nature of mine residue: Arsenic residue.

Rehabilitation objective: Safely contain arsenic-rich residue.

Rehabilitation earthworks: Pits excavated, lined with HDPE liner and basal drain installed prior to residue disposal. Once full, the top of the pit is sealed with HDPE liner and a topsoil growth medium applied.

Revegetation: Trees planted in growth medium after sealing.

Erosion control: Vegetation, benches and concrete toe channels.

Monitoring: Seepage from internal drain returned to treatment plant. Perimeter ground water wells monitored for signs of possible contamination.

Learning points:

- Benefits of removal of potential pollutants from bulk of the tailings material and concentration for disposal in fully lined facilities.
- Conversion of arsenic at plant into potentially less harmful oxidation state.



Arsenic residue disposal pit ready to receive waste material. Note the HDPE liner on the sides of the pit and the basal drain with collector sump for seepage recovery and treatment.



Same view of the residue disposal pit but containing some residue. Note the extension of the HDPE liner further up the side of the pit.

SUNRISE DAM

Mineral mined: Gold.

Mining company: AngloGold Ashanti (Australia) Ltd.

Location: Laverton, Western Australia.

Climate: Great Victoria and Gibson Desert climate. MAP: 230mm.

Nature of mine residue: Metallurgical plant tailings.

Rehabilitation objective: Formation of gentle-sloping tailings facility that is amenable to sustainable closure.

Rehabilitation earthworks: It is envisaged that the surface of the facility would need to be clad with waste overburden material upon closure at an estimated cost of around A$40.000/ha.

Timing: Upon decommissioning.

Weed and feral animal control: Electric fence to prevent kangaroo access during facility operation.

Erosion control: Perimeter berm and seepage collection trench.

Other details: Hyper-saline ground and process waters.

Learning points:

- Dust from crystallisation on surface of tailings could be a problem for surrounding vegetation.
- Large footprint to rehabilitate.
- Low energy facility.
- Slopes are flat and are more readily rehabilitated.

SUNRISE DAM (CONTINUED)



Aerial view of the Sunrise Dam mine site. Note the salt pans in the foreground, the waste overburden dumps around the open pit and the tailings facilities at the top of the photograph. The original paddock or cell tailings facility is in the upper centre of the photograph and the new CTD facility is in the upper right-hand corner.



Perimeter seepage interception trench. The CTD is to the right of the photograph.



Photograph taken immediately inside the perimeter berm showing the collection of storm water from recent heavy rains.



The access ramp to the central discharge point and the toe and basin of the facility.

SUNRISE DAM (CONTINUED)



Thickened tailings beach flow. Note the salt crystallisation in places on the beach and the consolidation cracking.



View taken looking up the access ramp.



Erosion channel from the discharge of low density tailings at times. Note the waterlogged toe.

THICKENED TAILINGS EXAMPLE

Mineral mined: Kimberlite/diamonds.

Location: Kimberley, South Africa.

Climate: Continental climate with hot, wet summers and mild dry winters. MAP: 420mm.

Nature of mine residue: Metallurgical plant tailings generated from the retreatment of dumps.

Area to be rehabilitated: Original slimes cell slimes dams via the deposition of thickened tailings from the combined retreatment plant.

Rehabilitation objective: Maximise tailings disposal capacity whilst generating a facility profile that would be more amenable to closure.

Rehabilitation earthworks: Use of tailings to change profile of original slimes dams.

Revegetation: Nil to date – kimberlite tailings material however is relatively simple to vegetate as it is inert.

Erosion control: Nil to date.

Learning points:

- Use of thickened tailings to rehabilitate old slimes dams whilst maximising capacity.
- Potential for thickened tailings material to be used to backfill open pits for closure.
- Difficulties of maintaining high slurry densities.
- High capital cost associated with dewatering and pumping high density materials.
- Importance of assessing full life-cycle costs of tailings deposit including those associated with closure and after-care.

THICKENED TAILINGS EXAMPLE (CONTINUED)



Aerial view of the open pits and waste dumps around Kimberley.



Thickener erection at retreatment plant.



Positive displacement pumps for the delivery of thickened tailings to the tailings facility.



Thickened tailings discharge stack at tailings facility.

THICKENED TAILINGS EXAMPLE (CONTINUED)



Thickened tailings material spreading out over the old slimes dam surface. Note the relatively dry state of the thickened tailings.



Thickened tailings material flow across the old slimes dam.

APPENDIX – CASE STUDIES

(ALTERNATIVE CASE)

BROCK'S CREEK

Mineral mined: Gold.

Mining company: AngloGold Ashanti Australia Ltd.

Location: Northern Territories of Australia.

Climate: MAP: 1.100mm MAE: 3.200mm.

Nature of mine residue: Fine tailings.

Area rehabilitated: Tailings facility.

Rehabilitation objective: Mine closure.

Rehabilitation earthworks:

- Waste overburden material end-tipped into exhausted open-pits.
- Slurry deposition into pits.
- Waste overburden material spread over top of tailings facility basin as a capping layer.

Erosion control: Waste rock spread over tailings facility surface.

Other details: Use of plastic bin liners on basin surface to act as a capillary-break beneath the waste rock capping layer.

Learning points:

- Use of tailings slurry to backfill exhausted open-pits as part of reclamation plan.
- Need to allow for long-term consolidation of tailings especially in filled pits.
- Must demonstrate the long-term performance of innovative ideas.

BROCK'S CREEK (CONTINUED)



Waste rock material end-tipped into exhausted open pit. Tailings slurry deposition into pit. Note the high water table.



Tailings facility – waste rock material stockpiled against upstream face of the impoundment wall for basin capping.



View along crest of tailings facility. Note waste rock material stockpiled against impoundment wall for basin capping and also the vegetation establishment on the downstream face.

BUTCHART GARDENS

Mineral mined: Limestone.

Location: Tod Inlet, Vancouver Island, British Columbia, Canada

Climate: Cool Mediterranean. MAP: 950mm. Quarry microclimate.

Area rehabilitated: Disused limestone quarry.

Rehabilitation objective: Rehabilitation of the disused quarry by owner's wife.

Rehabilitation earthworks: Topsoil from neighbouring farmlands used to line quarry floor.

Timing: 1904 to date.

Other details: Quarry bloomed under personal supervision and became the Sunken Garden.

Learning points:

- Sustainable closure of a disused quarry that continues to be run as a family business to this day.
- Success was the result of dedication and passion coupled with the creation of an end-product of beauty and international interest.

References:

http://www.butchartgardens.com/main.php

BUTCHART GARDENS



Portland cement factory at Tod Inlet on Vancouver Island.



Snow covering the Japanese Garden within the disused limestone quarry.



Sunken Garden within the disused quarry in summer.



Japanese Garden in summer.

EDEN PROJECT

Mineral mined: Kaolin (China clay).

Organisation: Eden Project Ltd.

Location: St. Austell, Cornwall, United Kingdom.

Climate: Humid tropics, warm temperate and semi-arid biomes.

Nature of mine residue: Disused China clay pit.

Rehabilitation objective: Sustainable closure coupled with business opportunity.

Rehabilitation earthworks: 850.000m^3 of excavation and filling, storm water drainage and slope stabilisation.

Revegetation: Wide variety of tropical and Mediterranean species from around the world in a sheltered micro-climate.

Timing: Opened in March 2001.

Erosion control: Storm water drainage and slope stabilisation.

Learning points:

- Definition of an appropriate and sustainable end-use for the closure of a disused pit in a project that boosts the local economy.
- The complex is below the surrounding ground level reducing its aesthetic impact.
- Civil engineering input included computerised ground modelling within a steep-sided quarry.
- Foundations for biome structures follow the complex contours of the pit.

References:

http://www.anthonyhuntassociates.co.uk/eden-project.htm

http://www.cornishlight.co.uk/the-eden-project.htm

EDEN PROJECT (CONTINUED)





Erection of the Geodesic domes within the disused quarry.



The completed biomes.



Interior of one of the completed biomes.

IDUAPRIEM

Mineral mined: Gold.

Mining company: AngloGold Ashanti Ltd.

Location: Southern Ghana, West Africa.

Climate: Tropical, warm and humid. MAP: 2.000mm.

Nature of mine residue: Waste rock overburden material.

Area rehabilitated: Open pits to be rehabilitated after filling with tailings material.

Rehabilitation objective: Dispose of tailings and fill disused pits.

Rehabilitation earthworks: No special earthworks.

Learning points:

- Use of disused pits to dispose of tailings whilst closing pits.
- Long-term consolidation of tailings and associated problems with final capping.



Disused pit prior to tailings deposition.



Pit receiving tailings.

PASTE EXAMPLE

Mineral mined: Gold.

Location: North-western Tanzania.

Climate: Equatorial modified by highland plateau. MAP: 1.000mm MAE: 1.900mm.

Nature of mine residue: Metallurgical plant tailings – flotation only – no cyanidation.

Potential pollutants: Acid rock generation.

Deposition technique: Cemented paste material produced for underground backfill and for surface disposal.

Learning points:

- Dewatering and deposition method produces an end-product that has natural slopes that should be more amenable to closure.



View of one of the four paste discharge stacks/towers – note no bleed water.



Flatter-than-anticipated beach slope necessitated perimeter wall raise. A steeper slope has subsequently been achieved with proper rotation of deposition between the towers.



Valves at discharge point and two towers visible on horizon.

TANAMI

Mineral mined: Gold.

Mining company: AngloGold Ashanti (Australia) Ltd.

Location: Tanami Desert, Northern Territories, Australia.

Climate: Desert climate. MAP: 350mm MAE: 3.600mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Paddock/cell tailings facilities and disused open pits.

Rehabilitation objective: Maximise tailings deposition capacity, create shape amenable to closure and backfill open pits.

Rehabilitation earthworks: Use of thickened tailings to minimise rehabilitation earthworks.

Revegetation: Nil to date.

TANAMI (CONTINUED)



Aerial view of the Tanami mine site with the three paddock/cell tailings facilities in the foreground.



Thickened tailings deposition in disused open pits. Note the slumping of part of one of the pit walls.



Thickened tailings backfill of a disused open pit.



View of the impoundment wall of a paddock/cell tailings facility.

TANAMI (CONTINUED)



View over the basin of a paddock/cell tailings facility.



View of tailings basin. Note the consolidation cracking and the salt crystallisation.



View over the basin of a paddock/cell tailings facility.



Central discharge point in basin of paddock/cell facility. Thickened tailings was used to change the slope from a concave to a concave profile to maximise capacity and form a shedding surface that is more amenable to closure.

UNION REEFS

Mineral mined: Gold.

Mining company: AngloGold Ashanti (Australia) Ltd.

Location: Pine Creek, Northern Territories, Australia.

Climate: Tropical. MAP: 1.100mm MAE: 3.200mm.

Nature of mine residue: Metallurgical plant tailings.

Area rehabilitated: Tailings facility.

Rehabilitation objective: Maximise depositional capacity, minimise closure earthworks and achieve mine closure.

Rehabilitation earthworks:

- Use of thickened tailings to change basin profile from sloping upstream to sloping downstream thereby maximising capacity.
- Application of waste overburden material.

UNION REEFS (CONTINUED)



Disused pit containing tailings.



Main impoundment wall of tailings facility.



Basin at the point where it meets the crest of the main impoundment wall. Note the waste overburden material used to cap the basin.



Waste overburden material and vegetation establishment on tailings facility basin.

UNION REEFS (CONTINUED)



View of tailings facility basin at decant.



View of waste overburden dump after rehabilitation work.



Face of waste overburden dump after planting.



View of basin of tailings facility after rehabilitation.

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