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Appendix A:
Large Volume Waste Working Paper

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1 Waste Disposal Options

All mining operations generate waste.[1] One of the most widespread management problems in the mining industry relates to the sheer volume and chemical composition of waste material handled. These very high volumes mean that where it is put and how it is managed are critical to determining the impact of mining.

1.1 Initial Considerations

Ore bodies are mineral enrichments in geological formations where extraction and recovery are profitable under current economic conditions. The required minimum grade of the enrichment, to represent an economic ore body, is dependent on the market price of a metal or mineral. Apart from the minimum grade, a host of other factors determine the viability of a project. These include: the cost structure (whether a deposit's shape and location make it amenable to low cost mining and processing methods), scale (high mining rate usually means lower unit costs), recoverability of the valuable mineral by processing (mineralogy, grain size of the ore mineral, hardness, impurities), and geotechnical setting (stability of underground openings, steepness of open pits, etc.).

Geological conditions determine the location of the ore body and the potential developer of the mine must evaluate the physical, environmental and social settings of the area to determine the feasibility of developing a mine. The technical evaluation of the geological, mining engineering and metallurgical characteristics of the deposit controls many of the decisions about its development. A very small percentage of attractive mineral deposits are finally developed as a mine.

Geological models for the origins of the ore body (including the geological history, the genesis of the deposit, etc.), mineral grades and the tonnages determine the technically and economically feasible mining method. For example, low grade disseminated ore bodies cannot usually be mined economically by underground methods; open pit mining is the most efficient way of developing such ore bodies. In most cases, more waste is generated during open pit mining than underground mining. This can be considered a positive aspect of open pit mining as it makes better use of the resource. Waste minimisation concepts should be incorporated in the design of new mines wherever possible.

Mineral extraction from the mined rock usually involves size reduction and other physical and chemical processes. The selection of a specific process must consider the metal to be recovered, the geological occurrence of the metal, the economics of the process and the environmental and social implications.

Different classes of extraction processes are used in the mining industry to recover metals from ore. These include physical separation that can consist of size reduction followed by gravity separation, to remove the heavier particles (such as gold). Hydrometallurgical processes involve the use of chemicals in water to dissolve, or otherwise remove, the metals

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[1] Note that 'waste' is used as a collective term for a number of components (such as overburden, waste rock, tailings, etc.) as described in Table A1.

from the ore. An example is the leaching of gold using a cyanide solution. The waste remaining from such processes contains various concentrations of the chemicals used unless treated. Re-circulation of process fluids is practised at some mines while treatment is usually carried out before discharge of solutions to the environment.

Flotation processes use special chemicals that allow the metals to be collected on froth for concentration. Lower concentrations of chemicals are used in flotation and most of it is consumed during processing. The resulting waste stream has a low concentration of these chemicals from a metallurgical perspective, but not necessarily from an environmental one. The environmental impacts of these chemicals are dependent on site-specific issues such as the nature of the chemicals and the presence of shallow groundwater.

It used to be normal practise to select the 'standard' recovery process, based on ore characteristics and previous experience, without giving particular thought to the environmental and social issues at a site. There are examples where both the mining and recovery method were re-designed following protests from environmental groups and other stakeholders. The New World Project in Montana, US, is one example. 'Moving up the pipe' to change the quality of the waste that is discharged has become an important strategy in many industries, including mining. This is an area where much progress has been made by many mining companies. Changes have made big differences in operational and long-term impacts.

'Waste' is a general term used to describe the various materials remaining at a mining operation after recovery of the metals. While other waste streams can be identified, such as liquid wastes, domestic solid waste, tires and other waste from the maintenance of equipment, laboratory waste, etc. this report will focus on the wastes of geological origin.

The terms used to describe various forms of waste and their definitions are given in Box A1. Some of these terms and definitions might vary in different parts of the world. Furthermore, there may be differences between the terminologies used in coal mining and hard rock mining (base metal, precious metal, etc.) and industrial minerals.

The volumes of mine waste produced in each category are dependent on the geologic characteristics of an ore body, the type of mining (underground *versus* open pit), and the metal being mined as well as the size of the mining operation. The following general comments can be made about the amounts of mine waste produced:

- Less mine waste is produced from underground mining operations than from open pit mining operations.
- Usually less tailings are produced from underground mining as ore grades are higher and tonnages lower.

Box A1. Terms and definitions for mine waste

Overburden	The rock above the mineral resource that must be removed in order to mine the mineral resource.
Waste rock	Barren or uneconomic mineralised rock that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of processing.
Low grade ore stockpiles	Rock that has been mined and stockpiled with sufficient value to warrant processing, either when blended with higher-grade rock or after higher-grade ore is exhausted, but often left as 'waste'.
Tailings	The solid product of the treatment and mineral concentration process that are considered too low grade to be treated further. Tailings are the finely ground host rock materials from which the desired mineral values have been largely extracted.
Heap leach spent ore	Rock remaining after recovery of metals and some soluble constituents through heap leaching and heap rinsing of ores.

- Mine production rates at typical open pit copper mines (and other base metal mines such as zinc mines) are higher than at gold and silver open pit mines so more waste is produced (note that in many cases gold and silver are associated with base metal ores and this Statement must be considered in that light).
- Very few mines produce all three types of waste (i.e. waste rock, tailings and heap leach spent ore).
- Often low grade ore that has been stockpiled is not processed and is then classified as waste. This material has a higher mineral content than other waste.
- The amounts of tailings produced at most precious metal and base metal mines is about the same as the amount of ore because the grades are so low. For example, a high grade gold ore body may contain tens of grams of gold per tonne while a high grade copper ore body may contain 2 percent copper per tonne (i.e. 20 kg/tonne). Therefore, even with very high efficiencies of recovery very little of the material is removed during processing and most of the original ore remains as waste. A mine producing 200,000 tonne/day of copper ore will therefore also produce close to 200,000 tonne/day of tailings.

Low-grade stockpiles contain ores that are sometimes used for blending during normal operations. However, they can contain ores that have uneconomical grades at the time of mining but have the potential to be economic if metal prices improve. They may be economic but be less profitable to process than higher grade ores available from the mine and therefore stockpiled until such time as the higher grade ore is depleted. These ores may be suitable for heap leaching at some mines but may remain in the 'waste' category at other mines and will have to be rehabilitated as such. Low-grade ore stockpiles may be placed in selected locations on other mine waste facilities, where they are easily accessible, or may be located on a central site near the plant. The main consideration with low-grade stockpiles is their chemical stability, especially in the case of sulphide ores (see Section 2.9).

Because of technological advances, it must be recognised that the waste rock and low-grade ore stockpiles of today could be the ores of tomorrow. This has been true throughout the last century and will most probably also be true in the future. For example, at the end of the 19th Century gravity separation and other less efficient processes were used for the recovery of gold. The remaining tailings contained a high grade of metals and some were re-mined in the 1930's and the remaining tailings still contained sufficient gold to allow economic recovery in the latter part of the 20th Century.

Two examples of large scale re-mining of tailings are the ERGO project in South Africa and Kaltails in Western Australia. In South Africa many of the old tailings storage facilities in the Johannesburg and surrounding areas are re-mined using high pressure water jets. The slurried materials are pumped to a central processing unit and the tailings are deposited in a large new facility further from housing developments (Anon, 1996).

In Western Australia a similar project, Kaltails, treated about 50 million tonnes of very dusty tailings near the city of Kalgoorlie-Boulder and placed them in a new facility with better dust control (Kalgoorie, 1998).

It is difficult to obtain detailed data on the production of mine waste on a national scale. Table A1 provides estimates of the tonnages of a range of different ores mined in 1995 and the percentage of that ore that becomes waste.

Table A1. World ore and waste production for selected metals, 1995.

Metal	Ore Mined (million tonnes)	Share of ore that becomes waste, not including overburden (%)
Iron	25,503	60
Copper	11,026	99
Gold	7,235	99.99
Lead	1,077	97.5
Aluminium	856	70

Source: Gardner and Sampat (1998)

The mass or volume of the mine waste produced is an indicator of the potential physical impact on the land surrounding the operation and not necessarily of the amount of pollution that may result (see the discussion on Pollutant Inventories, Section 2.9.7). It indicates the opportunity that mining companies have to consider alternative mine designs to minimise the overall volume of waste disposed of and the disturbance of additional surface areas. Backfilling of waste in open cast or strip mining is done routinely at many mineral sands operations in Western Australia and South Africa. Similar approaches are used in strip mining of coal. Mine pit backfilling is also an option in non-ferrous metal mining when there are multiple pits on a site or where the mine pit can be developed in multiple 'compartments'.

There has been an evolution of the terms used for the various disposal facilities. For example, disposal facilities for waste rock have been referred to as 'waste dumps', 'waste piles', 'waste rock disposal facilities', etc. For tailings disposal the terms 'tailings dams', 'tailings impoundments' 'tailings management facilities' and 'tailings storage facilities' have been used. The terminology chosen at a specific site reflects local practice but often also the sensitivity of the stakeholders to specific terms. 'Dumps' may have a connotation of disposal without care about construction methods, reclamation, etc. There may be a perceived need on a local basis to use different terms to describe the facilities. Similarly, the use of the word 'waste' has been questioned. Overburden is not a processing waste any more than material from a road cutting used for a highway fill is 'waste'. The term 'mine rock' is favoured over 'waste rock' in many areas, especially North America.

Terminology is often determined by local regulatory language, e.g. in California, the State Regulations refer to waste 'piles' and this term is commonly used in discussions in this State. Another consideration in selecting the terminology for a facility is to indicate its intended use. The term 'tailings dams' may imply that the facility will be used as a dam, a term usually reserved for water storage. Therefore, 'tailings dams' may imply that the facility will be used to store large quantities of water. In most cases, this is not good practice, especially if the structural design for the facility did not include this consideration. Many engineers therefore discourage use of the term 'tailings dams'.

In this working paper, the following terminology will be used: overburden, waste rock, tailings storage facilities and heap leach spent ore facilities. Typical characteristics of these facilities will be described below.

The physical and chemical characteristics and the disposal practices for the various types of waste are important in considering the potential use of the facilities following closure. Mine waste is considered as an economic burden on the mining operation and all efforts are made to reduce the cost of waste disposal. These large volume wastes provide significant opportunities for the development of a different mind set. They can be used to establish specially designed landforms that mimic the natural terrain near the mine, such as flat areas for agriculture, housing or industry. A good example of the latter is the tailings deposits that remained from placer gold mining in Sierra Foothills in California during the 1860's and 1870's. These relatively large flat areas are now extensively used for housing developments.

1.2 Location and Facility Siting

A large number of factors determine the location of mine waste facilities with respect to the ore body. This section presents a discussion of these factors from a technical perspective. The non-technical aspects are discussed in the Main Report of *Mining for the Future*.

Once the mining and processing methods have been established, selection of mine waste disposal sites and other facilities provides an opportunity for the long-term mitigation of environmental and social impacts to be addressed. This is an important tool for the mine developer that must be used in the pre-feasibility, feasibility and final design phases, making sure that the mine is designed for closure.

Rigorous site selection methods are available for the location of mine waste related facilities. It is essential that a multidisciplinary team consisting of mine developer, environmental professionals, engineers, social scientists and others work together in performing a site selection. The different perspectives involved in site selection are important.

The location of a mine will determine the potential options for waste disposal. It may be decided to consider land disposal, underwater disposal in lakes, man-made impoundments or oceans, in pit or underground disposal in mined out areas, etc. Ideally, a comprehensive siting study should be done without any pre-conceived ideas about a potential preferred option. Site selection should not be done in isolation from the selection of the most appropriate control and closure technologies (measures) that will be applied at each site. Sites unsuitable for use when applying one type of control and closure technology (i.e. slurry tailings) may be eminently suitable when another technology (such as stacking of thickened or paste tailings) is applied. Site and control/closure technology selection must proceed simultaneously.

Many trade-offs are made in selecting the location of a site for a specific facility. For example, the preferred site for a tailings disposal facility may not be the first choice of any stakeholder group (engineers, local communities, accountants, etc.) but a compromise of all views. At the extreme, there may be cases where the choice is between no mine and a mine with a tailings disposal facility in a location where there will be some impacts. This is not a threat but the reality and making that choice should be the job of all concerned, not least the local communities.

The basic physical steps in site selection for land disposal of waste, taking into account the climate of the area and other appropriate factors are (note: this approach can be extended to be more inclusive of all waste disposal siting issues):

- Identify the area of interest for locating the facilities. An example is: ‘a radius of 10 km around the ore body’.
- Identify the site and project specific factors that must be considered in the site selection, e.g. excluding sites in national parks, areas of mineralisation, consideration of wetlands and other sensitive environmental areas, the relative priority of economics and other factors, how local communities will be treated, etc. It is clear that the multidisciplinary project team must accomplish this task with input from regulatory personnel and stakeholders (including the communities that may be affected). Establishing clear siting criteria will make the rest of the process easier.
- Eliminate zones in the area of interest from further consideration based on the site and project specific siting criteria; this is also referred to as a fatal flaw screening.
- Perform a screening of the remaining area to identify possible locations of facility sites; this may result in 20 or more possible sites. List the characteristics of the remaining sites; physical characteristics, environmental issues and risks, social impacts (including the possibility of resettlement), relative capital and operating costs, etc.
- Develop conceptual plans for the intended use of the site using alternative development, control and closure technologies. Select the most appropriate technology for each site.

- Perform an alternatives analysis of the sites, with the associated best technology, using qualitative or quantitative methods.
- Investigate the remaining sites in more detail, i.e. field reconnaissance, mapping, drilling, etc. Expand the conceptual plans for site development using the most appropriate control, closure technologies and do the final alternatives analysis and selection.

There is a greater possibility that the optimum sites will be selected when a rigorous approach is used. Another significant advantage in using a rigorous, well-documented approach is that it provides a basis for review of the methodology and results. It is therefore a tool for use during consultation with regulators, surrounding communities and other stakeholders that should be on-going throughout the process.

2 Land Disposal

This section considers the conventional land disposal options for overburden and waste rock, heap leach spent ore and tailings storage facilities. Much information is available on these topics and it is not the purpose of this section to summarise or repeat this information. Tables in this section summarise useful reference materials on the various topics. The most important issues associated with these land disposal facilities are listed in this chapter.

Specific factors that play an important role in selection of sites include:

- **Economics**: There are economic advantages in locating the overburden and waste rock disposal facilities near the ore body because it will reduce the operating costs. It is common to transport tailings as a slurry and locating tailings storage facilities near the ore body is less important from an operating cost perspective. While there are operating cost advantages to locate heap leach facilities near the ore body, capital cost considerations (such as extensive earthworks) may dictate that the facilities be located away from the ore body.
- **Climate**: Mines are located in all climatic regions of the world from the Atacama Desert in Chile to high rainfall tropical areas of Indonesia to Polar Regions of Canada and Russia. Climate is a major factor determining the environmental performance of a mine and has a large impact on the site selection of facilities. Intercepting and storing large volumes of runoff can also affect the stability of facilities.
- **Site seismicity**: Seismic activity at a site is determined by its location. Much is known about the impacts of seismicity and dynamic loading on the performance of earthen structures. Specific attention must be paid to location of structures sensitive to seismic loading (such as tailings disposal facilities); their location and design must consider the potential risks posed downstream. The same is also true for pipelines.
- **Topography and hydrology**: Steep topography in the immediate vicinity of a mine often makes it very difficult to locate sites for the various facilities. While overburden and waste rock facilities may be located in steep terrain (with special attention to design and operating conditions), it is very difficult to locate tailings storage facilities in steep terrain when the tailings are transported as slurry. The size of an embankment in steep terrain will require a large volume of structural fill and may result in a very small

volume of the site remaining for waste disposal. This makes the storage capacity of the site inefficient. It is not uncommon to pump the tailings a long distance to a suitable site in flatter terrain. For example, in Chile one of the tailings storage facilities of El Teniente is 75 km from the mine. Runoff volumes at a site are determined by the precipitation upstream from the site as well as the area of the drainage basin. Placing the waste disposal site near the upper reaches of the drainage area will reduce the amount of runoff at a site that must be diverted or stored.

- **Surficial geology of site** (foundation conditions for facilities): Some sites may be ideal for storage of mine waste from a physical perspective while completely unsuitable based on the surficial geology. Thick layers of foundation materials having low strength and high compressibility may make it impossible to locate waste storage facilities, especially if the site is located in a high seismic zone.
- **Local communities and land use**: Not all ore bodies are located in remote areas where there is low population density. Very often, an ore body is located in an area where there are settlements and where the land use has benefit to these communities, such as agriculture. This presents an opportunity and an obligation to involve the communities in selecting the locations of the mine facilities and to get input in the design and final closure. For example, assume that the area near the mine does not have much flat area for cultivation; the overburden and waste rock storage facilities may be constructed in such a way to increase the flat area for cultivation. One example of this is the Misima Mine of Placer Dome. It may also be necessary to re-profile these facilities to allow future cultivation. Aesthetic values and impacts must be considered for placement of waste storage facilities. Mining changes the land use in an area and provides special opportunities for new thinking on post-mining land use. Using pre-mining land use as a basis for long-term land use planning may not be the best approach, although it is widely used. Local and regional land use may change during the mine life as a result of population influx, regulatory changes, etc. Flexibility in regulatory framework and planning at the mine site must be maintained throughout the mine life to make adjustments so that post-mining land use can be productive.
- **Other environmental issues**: Careful consideration must be given to all environmental issues, including protected areas and biodiversity. Using multidisciplinary teams for the site selection process will increase the awareness to these issues.

2.1 Overburden and Waste Rock Disposal

Intact rock is broken into smaller pieces in open pit mines by blasting. The broken material, referred to as run-of-mine waste rock, is removed from the pit by loading it onto trucks using loaders or shovels. Most overburden and waste rock disposal facilities at open pit mines are constructed with run-of-mine materials using trucks. There is very little control over the exact size distribution of these materials, however modern blasting technology allows considerable controls on the size of the largest particles. In-pit crushing of waste rock is done at a few mines. This is done to reduce the size of the material so that it can be transported by belt conveyors out of the pit to the disposal facility.

Often overburden and waste rock is end dumped from the trucks and the excess material is bulldozed over the storage facility edge to construct slopes at the angle of repose. The angle of repose is where the outer slope is just stable under the static loading conditions at the site and is typically 37–40°. These facilities can be constructed in multiple lifts or as one single lift; a decision usually made based on mining cost, physical stability and environmental issues. The overall slope of a number of shallow lifts is less than the angle of repose for a single lift. The thickness of a lift depends on the site conditions. For example, building a waste rock disposal facility in multiple lifts to enhance stability and environmental controls, in comparison to one lift may result in higher operating cost. However, the added environmental protection may make it compelling to select this option.

Overburden and waste rock facilities are constructed on natural terrain. Removal of topsoil prior to placing the overburden or waste rock is usually done to provide topsoil for reclamation of the facility. It is not possible to remove topsoil in very steep terrain or where there is very little topsoil (for example in desert terrain). Overburden and waste rock are not typically placed on lined foundations because of the cost and stability risk.

Waste rock storage facilities vary in height depending on the topographic conditions at the mine site. These facilities can be as high as 500 m in steep terrains. There are challenges associated with the stability and behaviour of such high facilities. In the late 1980's and early 1990's, British Columbia's Department of Mines and Energy (Canada) sponsored a series of studies on waste rock disposal facilities, which refer to the high facilities in the South-Eastern BC coalfields. Box A2 provides a list of these reports and other compilations on waste rock disposal (also refer to Box A4).

Box A2. References on Waste Rock Disposal Facilities.

Hustrulid, W.A.; McCarter, M.K. and van Zyl, D.J.A. (Eds.) (2000) *Slope Stability in Surface Mining*, Society for Mining, Metallurgy, and Exploration, Inc., 442p.

Hutchison, I.P.G. and Ellison, R.D. (Eds.) (1992) *Mine Waste Management*, Sponsored by California Mining Association. Lewis Publishers, Boca Raton:Florida. 654p.

Marcus, J.J. (Ed.) (1997) *Mining Environmental Handbook*, Imperial College Press: London. 785p.

McCarter, M.K. (Ed.) (1985) *Design of Non-Impounding Mine Waste Dumps*, Society of Mining Engineers, 216p.

British Columbia Mine Waste Rock Pile Research Committee (1991) *Investigation and Design of Mine Dumps: Interim Guidelines*, Prepared by Piteau Associates Engineering Ltd., British Columbia Ministry of Energy, Mines and Petroleum Resources.

British Columbia Mine Waste Rock Pile Research Committee (1991) *Operation and Monitoring of Mine Dumps: Interim Guidelines.* Prep. by Klohn Leonoff Ltd., British Columbia Ministry of Energy, Mines and Petroleum Resources.

British Columbia Mine Waste Rock Pile Research Committee (1992) *Documentation and Evaluation of Mine Dump Failures for Mines in British Columbia*, Prep. by Broughton, S.E., British Columbia Ministry of Energy, Mines and Petroleum Resources.

Box A2 – contd.

British Columbia Mine Waste Rock Pile Research Committee (1992) Report on Methods of Monitoring Waste Dumps Located in Mountainous Terrain, Prepared by HBT AGRA Ltd., British Columbia Ministry of Energy, Mines and Petroleum Resources.

British Columbia Mine Waste Rock Pile Research Committee (1994) Mined Rock and Overburden Piles. Consequence Assessment for Mine Waste Dump Failures: Interim Report, Prep. by Golder Associates, Ltd, British Columbia Ministry of Energy, Mines and Petroleum Resources.

British Columbia Mine Waste Rock Pile Research Committee (1995) *Mined Rock and Overburden Piles. Runout Characteristics of Debris from Dump Failures in Mountainous Terrain: Stage 2: Analysis, Modeling and Prediction: Interim Report,* Prep. by Golder Associates Ltd. in association with O. Hungr, British Columbia Ministry of Energy, Mines and Petroleum Resources.

British Columbia Mine Waste Rock Pile Research Committee (1999) Rock Drain Research Program: Final Report/Prepared for Manalta Coal Ltd., Prep. by Piteau Engineering Ltd., British Columbia Ministry of Energy, Mines and Petroleum Resources.

Slope failures of high waste rock storage facilities in steep terrain can impact large areas due to run-out. Slope stability has therefore been emphasised in developing these facilities. Surface water controls, such as diversions or specially designed and constructed channels to limit erosion, are very important for waste rock disposal facilities in any terrain, but especially when it is steep. Runoff over waste results in sediment uptake in surface waters. Specially designed and constructed sediment control facilities must be installed to remove the sediment before discharging the water to streams.

The method of construction of overburden and waste rock disposal facilities may result in the generation of dust that could impact surrounding communities. Air quality monitoring and specific speciation of the metals in the dust will help identify this issue. Regular wetting of the active surfaces of the waste disposal facility may reduce the amount of dust generated. Completion of facilities and concurrent rehabilitation of completed areas can also reduce dust generation.

A major issue related to overburden and waste rock disposal facilities is acid generation if they contain sulphides. This is further discussed below in Section 2.9 on Chemical Stability.

2.2 Heap Leach Spent Ore

Heap leach facilities are constructed on lined areas (referred to as the heap leach pad) for collection of all the leach solution during operations. Low-grade ores are placed on the lined surface and irrigated with a dilute cyanide solution for the extraction of silver and gold and with a sulphuric acid solution in the case of copper recovery. Synthetic liners (geomembranes) are typically used in the construction of heap leach pads and ponds. The leach solutions are very valuable and, if they escape into the environment, can result in economic losses. Environmental impacts may result if leach solutions leaks into the foundation below the leach pad, especially if there is shallow groundwater or local surface waters at the site. While these facilities are designed on the 'zero-discharge' concept, it is very difficult to achieve.

The design, construction, operation and closure of heap leach facilities are described in many references published in the last 20 years). Box A3 provides a list of these reports and other compilations on waste rock disposal (also refer to Box A4).

Box A3. References on Heap Leach Facilities

Hustrulid, W.A., McCarter, M.K. and van Zyl, D.J.A. (Eds.) (2000) *Slope Stability in Surface Mining,* Society for Mining, Metallurgy, and Exploration, Inc. 442p.

Hutchison, I.P.G. and Ellison, R.D. (Eds.) (1992) *Mine Waste Management*. Sponsored by California Mining Association. Lewis Publishers: Boca Raton: Florida. 654p.

Jergensen, G.V. (Ed.) (1999) *Copper Leaching, Solvent Extraction, and Electrowinning Technology*, Society of Mining, Metallurgy, and Exploration, Inc. 296p.

Marcus, J.J. (Ed.) (1997) *Mining Environmental Handbook*, Imperial College Press: London. 785p.

van Zyl, D.J.A. (Ed.) (1987) *Geotechnical Aspects of Heap Leach Design*, Society of Mining Engineers. 86p.

van Zyl, D.J.A.; Hutchison, I.P.G. and Kiel, J.E. (Eds.) (1988) *Introduction to Evaluation, Design and Operation of Precious Metal Heap Leaching Projects*, Society of Mining Engineers, Inc. 372p.

Heap leach facilities are constructed in lifts of run-of-mine or specially prepared ores. Special preparation may include only crushing (primary, secondary and sometimes tertiary stages) or may also include agglomeration. In the case of gold and silver ores, agglomeration is done to bind fine materials together, or to coarse particles, to improve the percolation of the leach solution through the heap. It is common to use low percentages (by weight) of cement as a binder in this case. In copper heap leaching, sulphuric acid is used in agglomeration to reduce segregation of the coarse and fine particles when placed in the heap. When a leach solution is applied, ideally all the rock particles are contacted while unsaturated flow conditions are maintained. In the case of gold and silver, weak cyanide solution is used while sulphuric acid is used for leaching copper

Heap leach facilities can be constructed using three lay out options: on-off (or re-useable) pads, expanding pads or valley fills. In the case of on-off pads, the spent ore is removed after leaching and rinsing the spent ore at the end of the leach cycle. The spent ore can be placed on a secondary pad that is lined to allow further recovery of the metals or can be disposed of in an environmentally safe fashion. The unloaded pad is then re-used for fresh ore.

Expanding pads are constructed on relatively flat land and the area and/or height of the pad is extended to allow for the full capacity. Material is leached in place. Intermediate liners (of synthetic materials) between lifts are used at a number of copper leach facilities to limit the amount of leachate retained in the heap and to prevent reduction of heap percolation as a result of compaction by the overlying materials. Leachate is collected in ponds designed to accommodate the site-specific water balance and, after recovery of the metals, the chemicals in the solution are replenished and the solution is re-applied to the heap. The ponds are sometimes covered with nets or synthetic balls (typically high density polyethylene) to limit access by birds. A closed circuit is maintained for the leach solution. In wet climates, it is often necessary to discharge excess solutions to the environment. These solutions are not always treated prior to release and sometimes the treatment is not sufficient to remove the contaminants.

Valley heap leach facilities are constructed in steep terrain. A lined earthen embankment retains the leach material and solution is collected and stored in the heap. The leach solution is then pumped to the process plant for metal recovery. It is possible that storing the solution in the heap may results in higher hydraulic heads on the liner that could increase seepage losses if a leak should occur. Other controls, such as leak collection systems, can be included in the facilities to mitigate this concern.

After recovery of the metals from the ore, the heaps are closed. The remaining spent ore may contain some of the chemicals used in leaching the ore, as well as un-recovered metals, and will also be at higher moisture content than overburden and waste rock (see Appendix B for further details).

2.3 Tailings Storage Facilities

Tailings storage facilities have been used extensively during most of the 20th century to store tailings deposited as slurry. A wealth of information is available on the design, construction and operations of tailings storage facilities. Box A4 provides a list of some of these reports and other compilations on tailings disposal.

The prime function of a tailings storage facility is the safe, long-term storage of process waste with minimal environmental or social impact. The design of each facility is specific to the mining operation and site conditions. The design life of a tailings storage facility is effectively perpetuity, which means it should be able to survive in a stable form without human intervention. Tailings storage facilities are constructed over a long period and this must be reflected in the geotechnical stability evaluations. One of the most important issues is that stability analyses are done with the correct geotechnical assumptions.

Tailings facilities may be constructed using tailings sand or borrow materials for the embankment. The amount of coarse tailings material or suitable rock, as well as the regional seismicity, will govern the type of embankment constructed. The construction of the embankment is done in a series of lifts, during the operational life of the mine. Synthetic liners or compacted clay may be used to minimise seepage.

Box A4. References on Tailings Rock Disposal Facilities.

Aplin, C.L., and Argall, G.O. Jr. (Eds.) (1972) Tailings Disposal Today, Miller Freeman Publications. 861p.

Argall, G.O. Jr., (Ed.) (1979) Tailings Disposal Today, vol. 2, Miller Freeman Publications. 599p.

Association of State Dam Safety Officials and US Committee on Large Dams (2000) Proceedings of the Tailings Dams 2000 Conference, Las Vegas, NV, March 28–30. 482p.

Hustrulid, W.A.; McCarter, M.K. and van Zyl, D.J.A. (Eds.) (2000) Slope Stability in Surface Mining, Society for Mining, Metallurgy, and Exploration, Inc.. 442p.

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The tailings are slurried via pipeline to the facility and deposited via a single point discharge, spigots or a cyclone, when the sand fraction is being used to construct the embankment. In single point discharge and spigot systems the tailings are usually deposited to form a beach against the embankment with the liquid collecting away from it. This reduces the seepage and increases the stability. The level of the tailings pond is controlled by decanting any surplus liquid, also referred to as supernatant. This can be done through an embankment drain, decant towers or a floating pump. The liquid is then returned to the processing plant or discharged.

Tailings are readily eroded. It is best to store as little water as possible in the tailings storage facilities. Excess water has been the main cause in many recent tailings storage facility failures. The management of tailings storage facilities, including water, is crucial to their long-term performance. This issue is currently addressed through a number of recent or ongoing projects:

- Management of Tailings Storage Facilities. ICME compiled a review of international regulatory requirements and showed that these address some of the issues associated with the management of tailings storage facilities but that further work will be required to provide clear guidance on this topic. This topic is in the work plan for follow up by ICMM.

- The Mining Association of Canada (MAC) developed *A Guide to the Management of Tailings Facilities* that is getting wide application in Canada and other jurisdictions. A follow-up study is currently underway.

The paper in Appendix F by Martin *et al.* was specifically prepared for this study, to provide further details on the stewardship of tailings facilities. The major topics considered in this paper are:

- Background and history of tailings dams
- Unique features of tailings dams
- Tailings dam failures
- Recent initiatives and trends – management aspects
  - Mining Association of Canada
  - Canadian Dam Association
  - International Committee on Large Dams and Related Organisations
  - International Finance Corporation and International Standards
  - United Nations Environmental Programme/International Council on Metals and the Environment
  - Initiatives by mining companies
  - The role of tailings facility design consultants
  - Regulatory trends
- Recent trends – tailings handling technologies
- Recent trends – metallurgical aspects of tailings management

2.4 Co-disposal of Mine Wastes

Design, construction and operation of mine waste facilities is well understood when the materials are placed in different facilities. In doing so one has to be satisfied with the inherent characteristics of the materials. By mixing some mining wastes, one may be able to 'manufacture' materials with modified, more desirable characteristics than those of each of the separate materials.

Co-disposal typically involves combining tailings and waste rock, with the coarse particles arranged in loose contact and tailings filling the voids between them. Co-disposal can be achieved by co-deposition or by combined pumping. Co-disposed materials are better graded than separately disposed wastes, resulting in improved engineering parameters and behaviour. For example, experience has shown that co-disposed materials have a reasonably high permeability (less than waste rock but equal to or greater than tailings) that permits rapid settlement, drainage and strength gain together with a reduced storage volume, greater water return, and greater opportunity for progressive reclamation (Wilson *et al.*, 2001).

Co-disposal by spraying tailings slurry over loose coarse waste was tried in South Africa's Witbank Coalfields where the tailings solids were found to penetrate about 0.3 m into coarse discard (-50 mm). Co-disposal by pushing coarse wastes into wet tailings was tried in Australia's Coalfields successfully creating a highly trafficable surface. The combined pumping of coal washery wastes (silt-sized tailings and typically –50 mm coarse reject, with a median particle size of about 10 mm) was initiated in Australia at Jeebropilly Colliery in South East Queensland in 1990. A natural analogue to the beach formed by pumped co-disposal is an alluvial fan. Alluvial fans are formed when an upland drainage emerges perpendicular to a valley. The lack of confinement results in relatively steeply sloped, coarse-grained, semi-conical fans comprising particles up to 150 mm in size, sloping at about 1 in 8.

Understanding the structure and conceptual flow model for waste rock disposal facilities is a critical issue with respect to developing analytical techniques to predicting their performance for closure and decommission. While this is an important task that must be carried out, it is necessary to look for new solutions. For example, rather than construct waste rock disposal facilities that promote oxidation, it may be possible to control the physical properties of the material in the disposal facility such that oxidation is restricted. New studies are underway to develop a material science for blending tailings and waste rock to provide new high strength materials with the hydraulic properties of tailings.

It is also possible to get the worst of both sets of characteristics from the co-disposed material. For example, tailings are sensitive to dynamic loading related to seismic activities. Waste rock is more prone to acid generation than tailings (see discussion below) because the open pore network allows for ready advection of air through the waste rock in the disposal facility. Co-disposal of the materials can provide an improvement in both characteristics of the materials, i.e. an increased dynamic stability and less acid generation. However, because of uneven production rates of waste rock it is possible that one can create a material with characteristics opposite to that intended. For example, adding too much tailings to the waste rock may result in a facility with lower dynamic stability than that of the waste rock, similarly adding too little tailings to the mix may result in higher acid generation at the site.

International Network for Acid Prevention (INAP) sponsored a workshop to investigate the state-of-the-art for the co-disposal of tailings and waste rock. The workshop was held in Vancouver, November 27 and 28, 2000. Approximately 30 international experts attended the workshop. The workshop summary report (Wilson *et al.*, 2001) notes that:

"The workshop found co-disposal is being practised in the coal mining sector; particularly in Australia. However, most of those applications are in confined areas (e.g. tailings ponds or pits). Much is known about transporting coal tailings and waste rock slurries. In contrast, very little research has been conducted in the hard-rock mining sector. While there are some parallels between the coal and hard rock co-disposal applications, there are many differences".

It is concluded that more research for hard rock application is required and that practical methods of implementing co-disposal must be developed. It is stated that:

"There are two broad ways to implement co-disposal of tailings and waste rock:

1. *Create a low permeability cover for tailings ponds and waste rock dumps where sufficient natural borrow materials do not exist for a cover*

2. *Build a co-disposed tailings and waste rock dump to create a single mass so that a tailings impoundment is not required*

Covers have the highest probability of success and should be pursued as a priority."

INAP has embarked on sponsored research to investigate various aspects of co-disposal. Literature searches have been conducted on the general topic of co-disposal as well as the use of co-disposal to reduce infiltration at the time of closure. Two specific areas of research is the construction of facilities for co-disposal of tailings and waste rock and the use of co-disposal methods to construct covers for waste rock disposal facilities. An extensive material characterisation programme has been undertaken.

2.5 Thickened Tailings and Paste

As with all areas of large volume waste disposal, the terminology about thickened tailings and paste tailings is not universal. A recent publication on paste and thickened tailings proposes the following classification system (Jewell *et al.*, 2000):

- A yield stress range of the order of say 200±25 Pa (at the point of discharge) is proposed as marking the transition between slurry and paste. The yield stress proposed is obtained using the vane-shear instrument.
- The term 'slurry' will in general apply to thickened tailings that will flow a sufficient distance from the discharge point for practicable, large scale above ground (surface) deposition. In a practicable system, even where positive displacement pumps are required to transport the slurry, the yield stress at the point of discharge will most likely be less than 200 Pa even if the material gets even more dense as it moves away from the discharge point.
- Slurries can be further subdivided according to the extent of thickening into low, medium, high and (possibly) very high-density slurry.
- The term 'paste' will in general be applied to ultra high-density thickened tailings with low flow characteristics and appropriate viscosity. At present pastes are mainly prepared for underground mine backfill uses, but providing a practicable deposition system can be designed to suit the flow characteristics of the paste, surface disposal operations may increasingly utilise this consistency of material in the future.
- The transition between a paste and cake can be defined subjectively as the material changes from a plastic 'paste' to a semi-solid 'cake'. This transition also probably delineates the maximum consistency that can be pumped by positive displacement pumps, although there may be exceptions to this rule of thumb.

Two other terms that have been used are 'dewatered' tailings and 'dry' tailings. Both of these typically refer to tailings that have been dried using a belt filter or filter press.

Conventional thickeners are typically used to increase the density of tailings slurries to produce thickened tailings. Densities of about 65% solids (and maybe a little higher) can usually be achieved with this type of equipment. Such dense slurries can still be pumped effectively and may form a relatively steep slope of up to 5% when deposited. Robinsky (1979) proposed central point deposition for such thickened tailings, thereby constructing a cone-shaped deposit. A few mines implemented this approach but it has not been widely accepted due to the difficulty in achieving adequate and consistent thickening, and of transporting the thickened tailings.

Specially designed deep thickeners have been developed to produce paste with special pumping systems used to place this material as backfill in mines (using cement to provide further strength and appropriate rheological characteristics to the material). The Bulyanhulu mine of Barrick Gold in Tanzania uses a paste surface disposal system. There are considerable potential advantages in using dewatered or paste tailings:

- Overall less fresh water use by the plant because more water and reagents are returned from the dewatering step.
- Tailings deposits that can be reclaimed as they are constructed. The surface should be fairly trafficable to allow access for equipment.
- Very little excess water on the tailings disposal facility, which means that the facilities are more stable and do not have the same degree of seepage.

Not all these advantages are realised in the field. For example, ‘trafficability’ may remain poor in wet climates making it difficult to develop efficient distribution systems for field placement. Extensive research and conceptual engineering on the material characteristics and the application of paste tailings for surface disposal of large volume waste is currently taking place.

The development of large capacity vacuum and pressure filter technology has presented the opportunity for storing tailings in a dewatered state. The filtered tailings are dewatered to a moisture content where they can no longer be pumped and are transported by conveyor or truck. They are then spread and compacted in an unsaturated, dense and stable ‘dry stack’ that does not require a retention dam. This method of disposal has a number of advantages such as (Davies and Rice, 2002):

- water conservation;
- recycling of process chemicals;
- lower seismic risk;
- co-disposal with waste rock;
- small footprint; and
- less environmental risk.

2.6 Backfill

Backfilling of mine waste into underground workings or open pits has certain advantages and disadvantages. A major advantage is that waste will be placed below the ground surface and will therefore not take up further space on the land. Waste rock and tailings used to backfill underground mines also improve the stability of the underground workings and minimises post-operational subsidence. As a result of the increase in volume of the waste rock when excavated, as well as the requirement to leave some remaining openings underground to provide access to the ore, it is not possible to backfill all the materials removed. Up to about 60% of the waste can be replaced underground; the rest is usually placed in surface disposal facilities.

Backfilling of mined pits is only possible in some cases where there are separate pits or an elongated pit or open cast. There are a number of mines where pits have been partially or completely filled with waste rock. In some instances, this approach may result in greater environmental impacts than leaving the pit open, such as when the waste and pit walls are highly acid generating and a steady water level cannot be maintained in the pit, or where the regional groundwater is recharged from the pit.

There are also concerns about covering up potential future resources. Low-grade mineralisation at the bottom of the pit is effectively removed from future exploitation. Double handling of materials for disposal can be a very important economic issue; therefore, it is not cost effective to backfill a pit at the end of operations unless there are very specific environmental and other advantages. Placing acid generating waste beneath a stable water table in the mined out pit can stop acid generation and provide for a long-term solution to chemical instability.

2.7 Physical Stability

2.7.1 Acute Physical Stability Issues

Maintaining the geotechnical stability of mine related structures during their operating life is paramount. This is especially true for waste rock and tailings storage facilities and heap leach piles. While each of these contain different materials and water conditions, the principles remain the same. Experienced geotechnical engineers should be responsible for these stability evaluations. Although many computer programs, that are relatively easy to operate, are available on the market the selection of the shear strength parameters and other material characteristics and the interpretation of the results must be done by an experienced geotechnical engineer.

The overall stability of mine waste and heap leach facilities are dependent on the foundation conditions, the characteristics of the materials in the structure, the water pressure (also referred to as pore pressure) in the facility and the potential for seismic events at the site. Tailings facilities that contain large amounts of water may also be vulnerable to overtopping. Tailings are readily eroded. Any over-topping may result in the containment being washed away, resulting in the failure of the facility.

The critical element for the geotechnical stability of a heap leach facility is the shear strength of the interface between the liner and the overlying or underlying material. This must be evaluated on a site-specific basis.

The containment for tailings storage facilities must be designed to withstand the potential loading conditions on a site-specific basis. Much has been published about this as is illustrated by the references in the Appendix F. Despite all this information, the designer of a tailings storage facility has a special responsibility to make sure that the correct parameters and design approaches are used in the analyses. It is good practice to have review boards with broad experience oversee the design of critical facilities.

One of the most important concerns, with respect to tailings storage facilities, is the large number of well publicised failures in recent years.[2] These failures have created concern at all levels as shown by the following quote from a letter that the Catholic Bishops of the Philippines sent to their President in 1998, "*We have seen the devastating effects of some of the mining operations: the spillages of mine tailings in Boac, Marinduque, in Sipalay and Hinobaan, in Negros Occidental, in Itogon, Benguet and mudflows in Sibutad, Zamboanga del Norte. The adverse social impact on the affected communities, specially on our indigenous brothers and sisters far outweigh the gains promised by large scale mining operations*."

There is no world-wide registry of tailings disposal facility failures and previous summaries or lists have focused on a wide range of 'failures'. For a mining company a 'failure' may imply some operational concern that makes it impossible to further deposit tailings in a facility, while at the other end of the spectrum, 'failure' may mean the catastrophic failure of containment resulting in release of tailings and human fatalities and/or extensive environmental damage.

Bulletin 121 of International Commission on Large Dams (ICOLD 2001; jointly issued with UNEP) documents 221 incidents of failure of tailings disposal facilities since the end of the Second World War and provided analyses of their probable causes. This may the closest to a 'world-wide registry of tailings disposal facility failures' (Strachan, 2002). Appendix F also presents an extensive discussion of recent tailings disposal facility failures.

Past failures of tailings storage facilities have caused the death of workers and people in downstream communities. Of all the major disasters in the mining industry only tailings failures (and other waste disposal facilities, Aberfan and Buffalo Creek) have killed so many members of the general public. They have also resulted in environmental damage. The latter range from relatively small areas to very significant impacts. For example the Pinot Valley failure in Arizona resulted in a relatively small footprint of tailings, while the Los Frailes failure in Spain resulted in tailings being spread over a large area downstream of the facility.

In 1996 Rio Tinto initiated a two year review of mine waste disposal at 75 sites world-wide. The review included a desk top study of all sites followed by inspections of 26 sites. The results of the survey showed that in the ten years prior to the survey there had been a total of 16 structural failures (21% of the sites), ten of which involved tailings and five involved waste dumps. In addition, ten facilities were classified as High Hazard under the Western Australia criteria (Richards, 2001).

Lessons can be learned from all failures provided there is sufficient willingness by the mining company to allow a complete investigation of the failure and that the information is widely disseminated (this is often not the case because of intervention by the courts). Some of the causes are easy to explain while others are more difficult. It is the latter that result in

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[2] A list of recent failures can be obtained from http://www.antenna.nl/wise/uranium/mdaf.html

the most significant opportunities for learning about the behaviour of tailings storage facilities.

Environmental clean-up following the failure of a tailings storage facility may include removal of all tailings released during the failure, e.g. the Pinto Valley Failure. It is usually very difficult to estimate the extent of such contamination before removal action, and large areas of natural vegetation may also be disturbed in the clean up. It is possible that the cure can be worse than the illness if the work is done without careful planning.

2.7.2 Chronic Physical Stability Issues

The term 'chronic physical stability issues' is used to describe ongoing symptoms that may not result in a catastrophic failure but that could reduce the overall stability of the facility in the long-term. The most significant of these is ongoing seepage that may lead to larger local failures or the development of preferential flow paths resulting in ongoing release of tailings supernatant. Such water may be contaminated and result in long-term chronic impacts downstream from the facility.

2.8 Dust Control

Dust from the dry beaches of tailings storage facilities is a specific concern for nearby communities. Beaches of tailings storage facilities contain fine sand or silt size particles that can be easily removed by wind. Wetting of the beach or using special products to stabilise the surfaces has been implemented for temporary wind erosion and dust control. Long-term stabilisation requires a gravel cover or vegetation to be established. This problem is one of the major ones related to tailings storage facilities and adjacent communities especially in dry and windy climates.

Blowing dust can result in impacts on health through breathing, etc. as well as agriculture through metals uptake by plants. A recent project in Gauteng, South Africa addressed this problem.

2.9 Chemical Stability

Chemical contamination represents one of the most serious potential short and long-term liabilities for many mining operations in all parts of the world. Mine derived pollution is one of the causes of water degradation in many parts of the world. Sources of pollution from a mine site can include mine water discharge from underground and open pit mines and leachate or runoff from waste disposal facilities.

It is important to distinguish between contamination that arise from dispersion of processing waste and that arising from the transformation of the constituents and their dispersion. Some examples of the former include the impacts associated with the disposal of tailings such as smothering of benthos, sedimentation of riverbed habitats and turbidity associated with riverine disposal of tailings. Much of this chapter addresses the latter issue, i.e. transformation of constituents and their dispersion, i.e. acid drainage and neutral drainage.

When discussing chemical stability, the first and major environmental problem facing the minerals industry today in much of the world is acid drainage. The production and disposal of waste products from mining operations has caused serious impacts to the environment, especially to water resources in a large number of locations. In particular, the remediation of the impacts of acid drainage is very costly for both the mining industry and governments around the world. Liabilities have been estimated to be, C$ 2–5 billion in Canada, more than US$ 20 billion in the US, DM 13 billion for uranium mines in the former East Germany (a large part of which deals with acid generation issues), US$ 300 million in Sweden and A$ 60 million annually in Australia (Taylor, 1998). It has also been shown that if acid drainage appeared late in mine life, or after closure, the rehabilitation costs are likely to be considerably larger than those that occur during the mine life. During the mine life, acid waters can be mixed with the process water for treatment and other mitigation measures can be implemented to reduce the acid drainage.

A great deal of research has been carried out to improve the understanding of chemical stability issues, including work on acid generation prediction, prevention, treatment and mitigation. There are few (if any) areas in mining where so much information is available. This section summarises the impacts of acid drainage and process chemicals on the water quality but will not provide an extensive review of water quality issues associated with mining or chemical contamination unrelated to the disposal of mine waste.

A number of research initiatives and programmes currently exist aimed at the prevention and control of acid drainage. The best known of these is the Mine Environment Neutral Drainage (MEND) programme that was started in the 1980's by the Canadian mining industry, national and provincial governments. The initial programme concluded at the end of 1997 and in 1998 a three year follow-up was started called MEND 2000.[3] These programmes have been very successful at developing techniques that allow for an improvement in the quantitative prediction of AD. MEND has identified some of the greatest opportunities for reduction of liabilities (Box A5).

There are also co-ordinated efforts on acid drainage in other countries, such as the MiMi in Sweden and ADTI in the US. In 1998 a number of international mining and minerals companies announced the formation of an International Network for Acid Prevention (INAP) designed to promote research and develop technologies to reduce the impact of acid drainage.[4]

The terms acid mine drainage (AMD) and acid rock drainage (ARD) are used in the literature. The former developed in the coalmines while the latter is mostly used in hard rock mines. For this working paper the term 'acid drainage' (AD) will be used to refer to both acid rock drainage and acid mine drainage. Because of the broad nature of acid drainage and neutral drainage, some researchers prefer the term polluted mine waters.

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[3] Details of the programme and the results can be found on http://mend2000.nrcan.gc.ca/

[4] Information on this work can be found at http://www.inap.com.au.

Box A5. Greatest opportunities for reduction of liabilities

MEND 3 indicated that an objective of this gap and opportunities analysis was to identify technology development that could lead to the greatest effective improvement in environmental conditions at mine sites as the MEND 3 program moves forward. To achieve this overall goal, further research should be applicable on a national basis, or should be applicable to a significant sector of the mining industry. The findings on technology gaps from the consultation were considered in this context.

The widest technology gaps were for:

- Underground mine geochemistry and geochemical modelling;
- Blending of any type (tailings and/or waste rock);
- Open pit geochemistry and modelling;
- Waste rock geochemical modelling (including waste rock hydrology and the behaviour of low reactivity wastes);
- Novel covers (de-sulphidized tailings, non-mining wastes);
- Permafrost; and
- Passive treatment systems.

The wide gaps for prediction of the chemistry of drainage from waste rock, underground mines and open pit mines partially reflects MEND's past emphasis on tailings, which has resulted in predictive models (such as RATAP) and significant reduction in the environmental impacts of tailings deposits. Geochemical predictions can currently be made for mines and waste rock but they are typically excessively conservative resulting in negative perception of the benefits of control and prevention technologies, possibly unnecessary contingency planning and high security deposits to cover uncertainties. More reliable prediction models for mine workings and waste rock would benefit all types of mines throughout Canada, though the primary benefit would be in Western Canada at underground mines in mountainous areas and the large open pit copper mines. This research would include coupled investigations of geochemistry, hydrology and limnology.

Development of blending of tailings and/or waste rock as a control technology has not occurred partly due to the limitations of waste rock modelling, which cannot currently predict the behaviour of heterogeneous mixtures due to the complexity of flow and chemical interaction in mixed waste rock and tailings. Blending potentially represents a walk-away technology without the long-term physical stability concerns of water and soil covers. In general, blending can only be implemented for new facilities at proposed mines and operating mines. Most of the current environmental liability in Canada is associated with historic mine sites. Research on blending would benefit proposed and operating mines.

Development of alternate cover materials would primarily benefit mines in areas lacking significant nearby deposits of soils with low permeability. Large number of historic mine sites in the shield regions of Eastern Canada would benefit from this research. These mines have deposits of acidic tailings but conventional soil covers are feasible due to the thin soil deposits. Alternate cover materials could include municipal wastes.

Box A5 – contd.

Finally, application of permafrost, or natural cold conditions as a control technology is at an early stage. The Northwest Territories and Nunavut are the only regions of Canada currently seeing significant development of new mines and these mines are in regions of continuous permafrost. Other proposed diamond mines are also in regions with some degree of permafrost (Northern Saskatchewan and Ontario). Low temperature technologies can also be applied to closure of mines in the far north by using natural or induced low temperatures. Research in this area would primarily benefit opening of new diamond mines, with a secondary benefit to closure planning for historic sites.

Water covers receive low weighted scores because the technology is thought to be well-developed. However, given the interest in long term performance of other technologies, SRK/SENES believes that the scores should be higher to reflect geotechnical (i.e. containment), climatological (i.e. climate change) and water quality related uncertainties. Using covers on oxidized material is also not well understood due to the development of reducing conditions that tend to de-stabilize oxide products.

Source: SRK Consulting and SENES Consultants Limited (2002)

2.9.1 Acid Drainage - Formation

Generation of acidic (i.e. low pH) drainage, typically containing elevated concentrations of trace metals, is the greatest water quality concern associated sulphide-bearing mine wastes. Release of trace metals with non-acidic drainage is a secondary concern. Acid generation begins in the circumneutral pH range when iron sulphide minerals (such as pyrite, pyrrhotite, marcasite) are exposed to, and react with, oxygen and water at the earth's surface. In the absence of one of these three components (sulphide minerals, oxygen, water) these releases will not occur. Water also serves as a medium to transport acid and trace metals in the environment.

As pH decreases below about 4.5, ferric iron begins to react with iron sulphides and the rate of oxidation and consequent acid production increases (Nordstrom, 1982). As pH decreases further, bacteria accelerate this reaction, and at pH 2 the bacterially mediated rate of pyrite oxidation is reported to be two to three orders of magnitude faster than the abiotic oxidation by oxygen. Thus, as pH decreases into more acidic regimes the rate of acid production increases substantially.

The degree of acidic drainage generation and the associated impacts are site-specific. The rate of iron sulphide oxidation and attendant acid production increases with increasing iron sulphide mineral surface area available for reaction, availability of oxygen, temperature and, as described previously, decreasing pH. The transport of acid and other reaction products from mine wastes disposed on the surface (as opposed to under water) will increase as precipitation (such as rainfall), surface water and ground water contacting mine waste increases.

The presence of alkaline minerals, particularly those containing calcium carbonate and magnesium carbonate, in mine wastes can neutralise acid and control or prevent acid drainage. Silicate minerals containing calcium, magnesium, sodium and potassium also dissolve to neutralise acid, but their rate of neutralisation is far slower than that of calcium carbonate and magnesium carbonate minerals. As long as the rate of acid neutralisation equals or exceeds the rate of acid production, mine waste drainage will not acidify. Consequently, sulphate and metals may be mobilised even though acid conditions do not occur. Mine waste drainage can remain neutral for several years then acidify due to decreasing rates of acid neutralisation or increasing rates of acid production (Lapakko and Wessels, 1995). Elevated concentrations of sulphate and metals may be precursors of acid drainage. They may also indicate a balance between acid-generating and acid-neutralising fractions of the waste material that effectively controls the transport of acid drainage to the surrounding environment.

Trace metals can be released from trace metal sulphide minerals reacting with oxygen (or ferric iron) and water and these reactions are similar to those of iron sulphides. These metals may remain in solution or react to form new solids. Dissolved trace metal concentrations tend to increase as drainage pH decreases (i.e. becomes more acidic). Nonetheless, concentrations of certain trace elements can be elevated in non-acidic drainages. Concentrations are largely dependent on the chemistry of the specific metal. Arsenic, antimony, molybdenum and selenium are among the elements that are more soluble in these drainages.

Release of acid or trace metals can occur wherever there is disturbed rock containing iron sulphide or trace metal sulphide minerals. This includes mines, whether underground or open pit, stockpiles, heap leach facilities, waste dumps and tailings storage facilities. Poor design and/or management of the waste disposal sites can facilitate the production and release of acid drainage into the natural environment. In instances where riverine disposal of waste has been practised, deposits of sulphide mine waste derived sediments on riverbanks (such as Clark Fork River in Montana, US) and coastal bays (such as Bougainville) may also produce acidic drainage.

2.9.2 Acid Drainage – Impacts

Acid drainage can present a number of potential problems during operations and closure including:

- Degradation of mine water quality limiting its reuse;
- Degradation of receiving surface waters;
- Impact of the aquatic ecosystem by acidity and dissolved metals;
- Impact on riparian communities;
- Possible impact on ground water quality;
- Difficulties in stabilising and re-vegetating mine waste; and
- Long-term water treatment costs.

One of the most serious aspects of acid drainage is its persistence in the environment. An acid generating mine has the potential for long-term, severe impacts on rivers, streams and aquatic life. Waste rock and tailings that have not been properly deposited or rehabilitated can produce acid drainage for hundreds of years or more after mining has ceased. Once the process of acid generation has started it is extremely difficult to stop and can effectively kill most living organisms in an entire water system for years, turning it into a biological challenge and a huge economic burden.

Acidic water easily dissolves metals such as iron, copper, aluminium and lead. These metals can produce a slimy substance (ochre) when the pH rises above 3.5 in the presence of oxygen, such as when acidic water mixes with water that is more neutral and the dissolved metals precipitate out as oxides and hydroxides. This in turn can accentuate the impact of acid drainage as the slime coats the streambed smothering the aquatic ecosystems.

There are many examples of sites and watersheds that have been damaged by acid drainage. This is a particular concern at abandoned mines such as the two watersheds being studied by the US Geological Survey in Colorado and Montana (see Appendix C).

2.9.3 Acid Drainage – Prediction and Risk Analysis

At new mining developments, the early recognition of the potential for acid drainage is essential for its successful management. The quality of drainage from mine wastes ranges from environmentally benign to highly acidic drainage with elevated concentrations of heavy metals. Prior to new mining development, projected mine waste must be characterised and their drainage quality predicted in order that mine wastes can be efficiently managed in a manner that avoids adverse impacts on natural waters. This also allows for the costs of mine waste management to be determined prior resource development and considered in the economics of mineral resource recovery (Lapakko, 1990).

The first steps are to, based on the mine plan, identify the rock types to be disturbed by mineral resource development and determine the quantities of rock types contributing to mine wastes. These materials are then subjected to characterisation through a series of evaluations that include:

- Evaluation of the site geology;
- Chemical analyses for sulphur, carbonate content, major components (whole rock) and trace metals;
- Mineralogical and textural evaluations that include thin sections;
- Static tests. Static tests evaluate the balance between acid generation potential (oxidation of sulphide minerals) and the acid neutralising capacity (dissolution of alkaline carbonates and other relevant minerals) (Environment Australia, 1997); and
- Kinetic testing. Kinetic tests involve site or laboratory tests that describe the weathering, due to exposure to air and moisture, of the material over time. These tests can provide indications of relative potentials for acid production, sulphide mineral oxidation rates, time period prior to the onset of acid generation, potential for metal release and the effectiveness of control techniques. Mineralogical analysis of weathered solids and

geochemical equilibrium modelling are assets in interpreting kinetic tests results and implications.

While there is extensive published information about these and other tests for the characterisation of mine waste and surrounding rock (Lapakko, 2002 - Appendix G to *Mining for the Future*), the interpretation of the results requires extensive experience. It is important that geochemists and hydrologists be involved with the overall design of the characterisation programme and the interpretation. It is further important that independent advisers be hired to validate the management plans and to contribute external expertise.

If the characterisation tests indicate an acid production potential then a risk analysis can be carried out to include the following:

- Characterise the acid generating potential of the materials;
- Characterise the sequence of production and disposal of different waste rock types;
- Characterise the mobility of metals and other potential contaminants;
- Estimate the potential for the migration of acid drainage; and
- Estimate the sensitivity and assimilation capacity of the receiving environment and therefore the consequences of the acid drainage.

The results of this analysis can then provide the framework for a risk management plan that includes the design and management of the waste retention facilities in order to minimise the production and migration of acid drainage and its impacts. An assessment should also be made of the uncertainties associated with current scientific knowledge about processes and modelling.

2.9.4 Acid Drainage – Control and Mitigation

Controlling or mitigating the effects of acid drainage at mine sites is based on a clear understanding of the site conditions and the development and migration of acid drainage. While it is possible to list ‘typical’ control and mitigation methods, they are always site-specific. Three basic approaches can be identified:

- Source control where one of the major components of acid drainage formation is eliminated making the possibility of acid generation very small;
- Migration control where acid drainage can still occur but measures are implemented that controls the migration of the generated acid; and
- Treatment where the acid drainage is intercepted and treated.

To control the production of acid drainage the potentially acid generating sulphide minerals must be isolated from water or oxygen. If this can be accomplished it can prevent or slow down the formation of acid or stop or reduce the release of the acidic discharge and pollutants into the environment. Complete isolation is not easily attained and there are definite long-term issues with the reliability of such an approach.

A very important alternative for acid drainage control and mitigation is the segregation of waste rock into potentially acid generating waste and non-acid generating waste. These materials can then be deposited separately. Alternatively, acid-generating waste can be blended with neutralising materials to mitigate acid drainage.

Engineered covers can be designed to minimise infiltration in a wide range of climatic zones. This is further discussed in the Working Paper on Mine Closure (Appendix B). In summary, a number of issues are important:

- Cover design is site specific depending on the climatic conditions, material availability and the sensitivity of the receiving environment;
- Covers can be separated in wet and dry covers; wet covers include water covers on tailings or other waste;
- Low permeability layers and capillary barriers may be part of covers, depending on the climatic conditions; and
- Evaporative covers can be designed to limit infiltration in areas where the precipitation is considerably lower than evapo-transpiration.

Water covers have been proposed for the long-term control of acid generation in tailings. The design and long-term integrity of the containment is a point of contention (Vick, 2000). The probability of something going wrong that may affect the long-term control of acid drainage or the stability of the containment may be quite high over the life of the facility.

Some mines return the reactive waste underground. Careful evaluations are necessary to show that the groundwater in the area of the mine will not be contaminated because of this waste.

While management to reduce the production of acid drainage is the most preferred option, it might be impossible to stop. The most common treatment method is the collection and mechanical treatment of the water with alkaline reagents such as limestone, hydrated lime and caustic soda. The appropriate reagent used is dependent on cost, availability and the target pH of the final effluent. Neutralisation is effective but has its drawbacks; maintenance of the system is costly, it treats the resultant effluent instead of avoiding production of acid drainage and it produces a separate sludge that requires careful disposal. This sludge typically has a very low density, however treatment processes are available that can increase the density of the sludge.

Other treatment systems include metal recovery and passive treatments systems. When present in sufficient concentrations, dissolved metals in acid drainage may represent an economic resource and can be recovered by solvent extraction or electro-winning (although this is rarely used). These processes can produce effluents that are more acidic than the conventional acid drainage and it will be necessary to neutralise the effluents. Passive treatment systems include the use of anoxic limestone drains, successive alkalinity producing systems and wetlands. In anoxic limestone drains the acid drainage flows through a constructed channel of coarse limestone gravel (that is covered) under anaerobic conditions. Experience shows that this treatment system has a relatively short effective lifespan as the alkaline materials in the drain will be consumed or coated, while a sludge or slime may form that requires ongoing maintenance of the system. Successive alkalinity producing systems avoid these problems by increasing the alkalinity in 'clean' drainage streams and then mixing these streams with the acid drainage.

Wetlands can provide an alternative low cost, low maintenance passive treatment system and can be combined with other treatment systems. Wetlands provide a wide range of physical, chemical and biological processes and microenvironments that can promote the removal of metals from acid drainage. These include the oxidation of dissolved metal ions and subsequent precipitation of metal hydroxides, bacterial reduction of sulphate and the subsequent precipitation of metal sulphides, the co-precipitation of metal with iron hydroxides, the adsorption of metals onto precipitated hydroxides, the adsorption of metals onto organic or clay substrates and metal uptake by growing plants. The design criteria for wetlands are dependent on the flow rates to be treated, acidity and metal concentrations in the acid drainage. The number of natural wetlands that have been documented to ameliorate mine drainage is extensive.[5]

2.9.5 Cyanide

The mining industry has been utilising cyanide for the recovery of metals for over 100 years. Although replacements for cyanide have been investigated, it remains the leaching agent of choice for gold extraction both in concentrator plants and in heap leach systems because of its efficiency. Although the knowledge of cyanide chemistry, analysis, environmental fate, toxicity and treatment has grown rapidly over the past decade, myths, misconceptions and fears still exist regarding its use. Cyanide, unlike some of the metals with which it combines, is not persistent in the environment. It readily oxidises or volatises unless present as metal or other complexes.

However, given the right conditions cyanide does react readily with other chemical elements forming compounds that are bio-available. Many cyanide compounds are known to be toxic to aquatic organisms and may persist in the environment for significant periods of time (Moran, 2000). Some of these toxic forms include metal-cyanide complexes, organic cyanide compounds, cyanates, thiocyanates and ammonia. It has been noted that many of these chemical species are not detected in the routine laboratory analyses and are often assumed not to exist.

Short-term exposure to high concentrations of cyanide, by inhaling, drinking, or eating contaminated substances, or by skin exposure is very toxic and can be fatal. There are very few examples of such occurrences in the mining industry. Cyanide is generally regarded as an acute toxicant but it is not carcinogenic, mutagenic or bioaccumulative (Mudder, 1999). It is not included in the most hazardous chemicals list of the US Environmental Protection Agency whereas in some countries (including Hungary), its use has been banned. In Montana, US, the use of cyanide in leaching operations is prohibited based on an initiative passed in 1998.

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[5] A list of some can be found at http://www.enviromine.com/wetlands/list.htm

Processes involving the use of cyanide, if not managed correctly, can have damaging effects on the environment. The effects include the killing of birds in heap leach pregnant and barren ponds as well as untreated tailings supernatant (Environment Australia, 1998); leakage from lined facilities; damage to the environment if released during failure of structures such as tailings disposal facilities.

There is a clear understanding for a need to effectively manage the use of cyanide in the mining industry. Environment Australia (1998) noted that best practice cyanide management should include:

- The establishment of a cyanide management strategy as part of the mine's environmental management;
- Implementing management training for workers;
- Instituting safe procedures for cyanide handling governing transport, storage, use and disposal;
- Integrating the mine's cyanide and water management plans;
- Identifying and implementing appropriate options for reusing, recycling and disposing of residual cyanide from plant operations;
- Developing cyanide monitoring programmes of the environment; and
- Establishment of carefully considered and regularly practised emergency procedures.

Important principles in managing cyanide effects on the environment include using the minimum effective amounts of cyanide required for metal recovery, safely disposing of cyanide in a way that eliminates or minimises environmental impacts and monitoring all operations, discharges and the environment to detect and deal with any escape of cyanide and subsequent impacts of that release. It is also essential to have emergency plans and procedures in place in the event of an accidental release of cyanide into the environment.

In order to address the concerns about cyanide management in the mining industry the Gold Institute, over the last two years, managed (on behalf of UNEP and ICME) the development of a cyanide management document known as the Cyanide Code. A multi-stakeholder committee was established to review and address the large variety of issues associated with cyanide transportation and use. The Code was released in mid-March of 2002 and is ready for implementation at individual mine sites. At present, an adoptive institution is being sought for the Code and third party audit has been planned but not yet started.[6]

2.9.6 Other Process Chemicals

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

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[6] See http://www.cyanidecode.org and http://www.mineralresourcesforum.org

Much information on the toxicity and environmental fate of chemicals that are commonly used in mineral processing is contained in Material Safety Data Sheets (MSDSs) which are provide by the suppliers of these products for industrial users. Whilst the focus of MSDS information tends to be on occupational exposures, handling and transport of the chemicals in use, there is also information on discharge to the environment, disposal of wastes and environmental effects. MSDS information is compiled by the supplying company but commonly references government and peer-reviewed science as its principle source of advice for users

Another issue is the potential toxic synergies between process chemicals, each of which has been tested as non-toxic. Site-specific combinations of chemicals must be evaluated for such effects when new formulations are introduced.

2.9.7 Pollutant Inventories

Pollutant Release and Transfer Registers (PRTRs), in some regions called Pollutant Release Inventories (PRI) or Toxic Release Inventories (TRI), are an increasingly powerful public policy instrument that provide valuable information to governments, the public and industry on potentially harmful releases of pollutants to air, water and soil. Facilities releasing one or more of the substances in excess of a predetermined threshold have to report periodically on what substances are released (McCauley, 1999). In addition, facilities are also required to report on pollution prevention activities, how much of the chemicals were transported away from the reporting facility for disposal, treatment, recycling or energy recovery and the efficiency of waste treatment. [7]

An obvious benefit of PRTRs is that with this information, as well as hazard and effects data, government authorities and industry can eliminate the most potentially damaging releases, plan to avoid problems and respond in case of emergencies. In this context, PRTRS provide an opportunity for companies to identify types of emissions, improve their environmental performance and communicate these successes effectively to the public.

PRTRs came into effect when more than 150 countries participating in the 1992 Earth Summit (UN Conference on Environment and Development, UNCED) in Brazil agreed that individuals should have access to information about the environment and have the opportunity to participate in making decisions, and that countries should encourage public awareness and participation by making information widely available. This was followed by the production of a guidance manual that was published for use by member governments with UNECD supporting international organisations in assisting non-member countries to consider PRTR programmes.

One of the biggest issues with respect to PRTRs is that of bioavailability of the substances that must be reported. For example, before a recent court ruling in the US it was necessary for mining companies to report the identified metals in waste rock as a pollutant or toxic

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[7] US EPA Toxic Release Inventory Program: Your Right to Know!
http://www.epa.gov/region09/toxic/tri/. Accessed 8th May 2001.

release, regardless of its bioavailability. This issue is controversial and both sides of the issue have made their concerns known

3 Riverine Disposal

The most controversial way of disposing of mining waste is in a river. Disposing of tailings or waste rock into river systems has been commonly practised throughout mining history and is currently used as a disposal method at a limited number of mine sites.

When riverine disposal was used in the past, little was known about the potential impacts and the protection of the environment was an unknown concept. Several historic examples exist; the Coeur D'Alene area in Idaho, US, the El Salvador mine near Chanaral Bay in Chile, the Clark Fork River in Butte, Montana, US and the Panguna mine in Bougainville, PNG.

Mines that currently use riverine disposal are located in the Asia Pacific region; BHP's Ok Tedi copper mine in Papua New Guinea, which has probably received the most publicity, Placer-Dome's Porgera gold mine in PNG's Enga Province, Freeport's Grasberg copper and gold mine in West Papua, Indonesia[8] and the Tolokuma Gold Mine in PNG. The continuing practise of riverine disposal is highly contested by environmental groups and other NGOs. In spite of a number of rational arguments in its favour, the fact that riverine disposal is used in developing countries, by multinationals that do not use the same method of disposal in their home countries raises a number of issues.

The main concerns with riverine disposal are that river ecosystems are highly vulnerable to the addition of excessive quantities of sediment. Sedimentation of the river bed creates major problems with flooding and the consequent rising of water tables downstream destroys riverine and floodplain forests and any associated agricultural developments. It is thought that this approach should be discounted on the grounds of sustainability as it leaves a massive environmental burden for future generations (Angel, 2000).

This chapter is based on a series of case studies of the mines mentioned above, three of which are contained in Annexes H, I and J. The case studies are intended to present a balanced description of the mining operation, including the criteria used for the selection of riverine disposal, the environmental and socio-economic impacts, the benefits of the mine and compensation, and a discussion of the decision-making process and drivers. These points are summarised here, with the exception of drivers and decision-making processes, which are discussed in the Large Volume Waste Main Report.

3.1 Criteria for Selection of Riverine Disposal

Historically, the main criterion for adopting riverine disposal was probably convenience and economics. Mining and processing operations were typically located near river systems that represented a cheap and handy waste disposal conduit. For example, between 1886 and 1997, at least 44 mineral treatment plants are known to have operated in the Coeur d'Alene river

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[8] See case studies in Appendices H-J.

basin in the State of Idaho, US. The proximity of these plants to the river system meant that riverine disposal was an easy way to get rid of wastes without incurring additional costs (although this was not done throughout the entire period listed above). This method of tailings disposal was legal in Idaho until 1968. Tailings were discharged to the streams, sluiced to the South Fork/Coeur D'Alene Rivers or discarded directly to the floodplain where they eventually eroded into the river system.

In recent years, the physical conditions at a mine site have been a main criteria for riverine disposal. Stable areas suitable for the land disposal of tailings may not exist near the mine, or seismic activity and high rainfall may threaten the stability of waste impoundments. These conditions have contributed to the selection of riverine disposal for all three mining operations where this method of disposal is currently being used. For example, at the Ok Tedi mine, construction was started on a tailings storage facility on a tributary of the Ok Tedi River. During the early stages of construction, the normal heavy rainfall (25 mm/day) combined with unsuitable geotechnical conditions, caused a landslide that destroyed the facility foundations. This incident showed that any tailings facilities in the area ran the risk of being destroyed. Riverine disposal of tailings became the disposal option by default at Ok Tedi. Section 1.2 describes location and facility siting options in further detail.

Economic criteria are also extremely relevant in the choice of disposal options. The infrastructure required for riverine disposal is minimal and, not including possible downstream rehabilitation, it represents the least expensive disposal method. The selection of riverine disposal may therefore be heavily based on cost. In some cases, a mining operation might not be economically feasible without these cost savings. How this criterion is balanced with socio-economic and environmental concerns is controversial, and is discussed in the *Mining for the Future Main Report*.

3.2 Environmental Impacts

Riverine disposal of mine waste is mainly contentious because of its environmental impacts. The environmental legacy of past mine waste disposal in rivers can be considerable. For example, the Coeur d'Alene area is now one of the largest US National Priority Superfund Sites. The transport of sediments by the river has resulted in the impacted area extending over 3,885 km^2 of the Coeur d'Alene River basin. It is estimated that it will take 20 –30 years to reverse the damage across the entire basin and federal officials say this will cost more than US$1 billion. The full cost of environmental impacts remains difficult to value; rehabilitation costs are only part of the picture.

Disposing of large volumes of mine waste into a river system will increase sediment load and result in the downstream deposition of sediments. The amount of mine waste currently discharged into rivers by the three operations under discussion is presented in Table A3. The scale of the impacts varies depending on the nature of the river. Impacts due to total suspended solid levels depend on the natural sediment load and deposition along the river system. In all three cases, wastes are discharged in rivers with relatively high natural sediment loads. For example, at a point approximately 140 km downstream of the Porgera mine, natural sediment load is such that the mine waste load in the river represents 25% to 33% of the total load.

Table A3. Mine waste discharged at riverine disposal sites

	Waste discharged (tonnes per day)		
	Tailings	Waste rock	Total waste
Grasberg Mine	220,000	–	220,000
Ok Tedi Mine	80,000	120,000	200,000
Porgera Mine	15,400	27,400–41,000	42,800–56,400

Source: see case studies in Annexes H, I and J.

Sediment deposition downstream of the mine depends on the size of particles and the nature of the river's flow. Coarse tailings and waste rock can deposit closer to the discharge point if the energy of the river system decreases sufficiently. Fine tailings are more easily transported through the entire river system. Sedimentation of finer particles occurs to a higher degree in the flatter reaches of river systems. Sediment deposition results in riverbed aggradation and over-bank deposition. For example, riverbed levels are reported to have risen 2–3 m in certain sections of the Porgera River and 6 m in the Ok Tedi.

Sediment accumulation in the riverbeds reduces flow capacity and increases the incidents and severity of over-bank flooding. Due to water logging and sediment deposition, the amount of oxygen is reduced such that vegetation along riverbanks is killed off. This phenomenon is called dieback and is a major impact of riverine disposal. Along the Ok Tedi, dieback has affected approximately 480 km^2 of the rainforest. In the Ajkwa River downstream of the Grasberg mine, sediment deposition has created a flood plain of 130 km^2. Sediment deposition will ultimately affect 220 km^2 of land, which has been set aside for tailings deposition in regional land-use plans.

Sediments that do not deposit along the river system are discharged in the delta or ocean. Coastal sedimentation of mine waste is also a potential riverine disposal impact. For example, mine waste in the Salado River from the El Salvador mine in Chile resulted in the creation of a 3.6 km^2 beach, made up of 150 million tonnes of mine sediments, in the Bay of Chanaral.

Riverine disposal of mine waste also introduces metals or other minerals into the river water as well as process chemicals, which may affect water quality. Fine sediments, in particular tailings, may increase heavy metal concentrations in the solid fraction known as the particulate load (or suspended solids). Metals and other elements may also be present in a dissolved form that is more easily bio-available. At different distances from the discharge point, the dissolved and particulate levels of lead, mercury, zinc and copper are of varying degrees of concern at Porgera, Grasberg and Ok Tedi. Discharging mercury into rivers can be particularly problematic as it is bio-accumulative and remains in the environment, as illustrated by some historic cases.[9] Water impacts can extend to groundwater, depending on the hydrological regime. This is not an issue at any of the present riverine disposal sites because of very high river flows.

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[9] At the Carson River in Nevada, mercury impacts persist in wetlands after 130 years.

Acid drainage from over-bank deposition of mine waste also affects water quality. It has been a problem at historical sites but does not seem to be a major issue at present riverine disposal sites. The buffering capacity of the highly alkaline tailings being discharged would effectively mask acid production; the regional geology also sometimes has a buffering effect. For example, at the Ok Tedi mine the presence of limestone in the ore body and waste helps maintain a neutralising environment. At Grasberg, ore and/or limestone are blended to ensure buffering capacity in excess of that which occurs naturally. However, the buffering effect may have a limited lifespan and acid drainage could become a long-term issue.

Measuring water quality is not always straightforward and involves a number of choices. Water quality can be measured against nationally established compliance standards, international drinking water guidelines (such as those of the WHO) or aquatic organism protection guidelines (such as those of ANZECC, USEPA and Environment Canada). The location at which water quality is measured is important because concentrations change in relation to the distance from discharge point, due to dilution, chemical reactions and the energy in the river system. The location of a compliance point may depend on the nature of the river, but can be controversial because of dilution. For example, at Porgera compliance is measured 165 km from the point of discharge. This location was chosen because of accessibility, traditional river use and the PNG government had operated a monitoring station there for a long time, thereby providing baseline flow data.

Riverine disposal may have significant biological impacts. Increased sediment loads and changes to the flow regime may change the number and population of aquatic species. For example, migratory fish may not be able to reach tributary rivers for spawning. Smothering of benthic fauna is a likely impact, as indicated in the case of Chanaral where inter-tidal invertebrates and most algal species were eliminated around the coastal discharge of the river. Metal uptake and the bioaccumulation of metals in freshwater or marine species are also possible. Water quality at Porgera, Grasberg and Ok Tedi is assessed through bio monitoring. Monitoring of metal uptake has so far shown that this is not an issue. The credibility of the monitoring results depends on the perceived degree of independence of the sampling and monitoring body. Terrestrial species can also be affected. In dieback areas, flora is eradicated, as is fauna that cannot move to new areas. River food sources for terrestrial animals are also affected.

The scale and long term nature of environmental and biological impacts depends on a number of factors; background conditions, climate, re-growth, re-colonisation rates of impacted areas (submerged or on land), species tolerance to sediments and metals, etc. In warm, tropical climates rates of growth are high, revegetation of tailings impacted riverbanks can be relatively fast, and alternative river habitats for aquatic species can help accelerate fish colonisation rates. In the Ok Tedi, risk assessments have predicted that displaced fish species that are still found in the tributary streams will return to the river when mining ceases and suspended sediment returns to its former level. Smothered benthic fauna sites can also be re-colonised by inter-tidal species. This has been the case at Chanaral Bay; fauna at the impacted sites have slowly been re-establishing themselves during the past few years.

3.3 Treatment and Rehabilitation

Treatment and rehabilitation measures help mitigate the scale of environmental impacts. For example, tailings from Porgera are treated before discharge to neutralise free cyanide, precipitate mercury, and trace metals. At Grasberg, a management system of levées was constructed to contain and control the river flow within a restricted area of the floodplain, thus limiting the affected downstream area. At Ok Tedi, trial dredging of the upper reaches of the river is undertaken to minimise the sediment build up that was causing dieback. This measure has enabled some recovery of dieback. In addition, revegetation studies and implementation plans exist for Ok Tedi and Grasberg. Revegetation trials of tailings impacted areas have yielded promising results because of the high recovery rate associated with the tropical climate.

A good example of the successful rehabilitation of a riverine disposal project is the Clark Fork River. The river system intermittently received mine waste up until 1982. Since then, a series of mitigation measures have been implemented including water treatment measures. The project ensures good water quality for downstream resource users, provides wildlife habitat and recreation areas, and has become a tourist attraction. However, all of this is being accomplished at considerable cost.

3.4 Socio-economic Impacts of Riverine Disposal

Environmental changes caused by riverine disposal inevitably have socio-economic impacts on downstream communities. Physical changes, such as degradation of water quality, widening of river channels, changes in flow, over-bank deposition of tailings and flooding can impose a number of alterations in community lifestyles.

The scale of these impacts depends on the pre-mine uses of the river. In areas that were not originally used because of inaccessibility, excessively fast flows, or naturally poor water quality, the socio-economic impacts are limited. This is the case in certain parts of the upper catchments of the Ok Tedi, Grasberg and Porgera river systems that are inaccessible and relatively uninhabited. This was also the case for the Salado River near Chanaral Bay, which had naturally poor quality.

Degraded water quality and increased sediment levels may prevent the use of river water for drinking and cooking. Changes in water quality necessitate using alternative water sources. This may or may not be problematic depending on water access in the area. In the Porgera area, the communities did not take water from the main river because of the high turbidity. However, downstream communities were issued with rainwater collection tanks to provide an easier source of water. Other potential uses of water are also affected, such as agricultural, irrigation, livestock or industrial uses. These impacts depend on the availability of alternative water sources.

Increased sediments and degraded water quality in river systems can also influence fish behaviour thereby affecting subsistence or commercial fishing. The discharge of sediments to the coast suggests that ocean fishing may also be affected although site-specific risk assessments must be done to investigate this.

Widened rivers and changes in the flow regime may alter river transportation and crossing points. Shallower, faster flowing water was reported to have resulted in transport difficulties for communities in the Fly River, above the junction with the Strickland River, which receives waste from the Ok Tedi mine. River crossing problems in Bougainville meant that bridges needed to be built to compensate for these difficulties.

Over-bank deposition of sediments, subsequent flooding and dieback can have severe impacts on local communities. At Ok Tedi and Grasberg, flooding and dieback have occurred over large areas. These lands were originally used for riverside gardening and hunting, and these activities are consequently reduced or not possible. At Grasberg, the land has been re-designated and the traditional use of hunting and gathering has changed. Some flooding and dieback has occurred outside this area. At Ok Tedi, lands were originally used for riverside gardening and hunting, and these activities are consequently reduced or not possible in these areas. Replacing these lost lands can be difficult in areas such as PNG, where land is traditionally owned and tightly controlled. When these consist of activities affecting livelihoods, alternative food sources and sustainable economic activities are necessary for communities to survive. The extent of socio-cultural changes and improvement measures has to be considered and addressed for communities not to suffer from the presence of a mine.

3.5 Mining Benefits and Compensation

In spite of the negative environmental and socio-economic impacts that may result from riverine disposal, countries and communities have sometimes welcomed mining with this type of waste disposal because of potential benefits. To counterbalance mining impacts, compensation payments are often offered to the local community in the form of one-off or regular cash payments, or regional development.

The presence of a mine can be a vehicle for development in remote regions. The benefits associated with a mining operation can include land rent, job creation and infrastructure development including roads, power production, water distribution, construction of schools, hospitals, etc. Even though riverine disposal may have known and perceived detrimental environmental impacts, these benefits can sometimes override local and national perceptions of a mining activities overall contribution to an area's development. An interesting example is the Ok Tedi mine. Although the operating company, BHP Billiton, has decided to withdraw from OTML because the mine is inconsistent with its Charter, the government and local communities manifest a keen interest in keeping the mine open. Trade-offs between economic, environmental and social impacts are discussed further in the Main Report of *Mining for the Future*

Royalty payments can represent a significant source of income and can involve substantial amounts of money. They are distributed to the national governments, regional governments or local communities. In many cases, they are paid exclusively to national governments that distribute them according to government policy and priorities. Royalties are a potential means for development, however they can be a source of conflict when regional governments and local communities perceive their distribution as unfair. Corruption may significantly contribute to this.

Compensation payments may also be used for regional development. This possibility, however, is dependant on the management and distribution of the payments. Payments may be one-off or paid annually, directly to specific individuals, such as landowners, or invested into funds for local development. Examples of such funds include the Freeport Fund for Irian Jaya in the Grasberg area. It commits 1% of the company's annual revenue to support development programmes for villages in the mining area.

The 'success rate' of compensation payments depends on local involvement. Decision-making on compensation distribution/fund management must be transparent and participative. An extensive consultative process is necessary in order to identify legitimate stakeholders, understand local needs and create accepted compensation distribution mechanisms. Communities that are involved in negotiations are not always the same as those that suffer downstream impacts. Fair compensation requires identifying all those impacted by riverine disposal including communities far from the mine site. In Bougainville for example, compensation mechanisms and benefit sharing in general were never accepted by the second generation of local landowners. This constituted the main reason the mine was forcibly shut down by a rebellion in 1989.

3.6 Risk Assessment

A risk assessment is essential in order to evaluate potential impacts, including the worst case environmental and socio-economic impacts, that may result from riverine disposal. The actual extent of the impacts of riverine disposal have often surpassed predictions. This can occur because of limited scientific knowledge and prediction errors. It can also result from changes in the project design. For example, major increases in production at Grasberg are resulting in different impacts to those originally anticipated. Mitigating unanticipated impacts implies taking into account changes in circumstances through ongoing or periodic risk assessments. The large percentage of error in predictions made by risk assessment models justifies requirements for monitoring and evaluation to identify if and when predictions are inaccurate. Monitoring and re-evaluations are also important in order to understand why predictions are inaccurate. For example, monitoring at Ok Tedi has significantly added to the understanding of the potential risks of riverine transport of mining wastes.

Accurately predicting riverine disposal impacts is important for a number of reasons. Planning and implementing impact mitigation measures depends on accurate risk assessments. Successful compensation negotiations depend on a sound knowledge of potential impacts and their extent. This is also vitally important in order to enter into any balanced negotiations on trade-offs between the economic, environmental and social impacts.

However, projecting the likely effects of changes associated with a new project on the behaviour of complex systems such as tropical rivers, beyond the range that can be observed, is extremely difficult. Models to perform these predictions produce estimates that are inevitable bounded by significant error bands. There is no realistic way round this, yet some estimate is necessary to make the case for any project and to develop agreed conditions under which impacts will be mitigated. Two elements can give more confidence in the use of models in these circumstances:

- Peer review of the models used, the data available and the assumptions used in generating the predictions. Independent experts should carry this out.
- There should be a binding and specific condition to validate the models over the initial period of operation of a new project. Adequate monitoring is needed to enable this validation, and the results should be used in a re-evaluation of the predicted impacts. Updated information may result in new permit conditions.

4 Marine Disposal

Marine disposal of mining waste is used at a number of mining and mineral processing operations around the world. Waste rock may be discharged at shoreline or to deeper water from a barge. Tailings and other process residues can be conveyed through a pipeline as a slurry and discharged at beach level or at depth via a submerged pipeline.

Marine disposal is sometimes considered as a disposal option at coastal and island sites, where viable land disposal options are limited or virtually non-existent. What is known as deep sea tailings disposal (DSTD), Submarine Tailings Disposal (STD) or Deep Sea Tailings Placement (DSTP), involves a different set of criteria and potential impacts than shoreline and very shallow water marine disposal. The environmental impacts of marine disposal and their acceptability to local communities, governments and civil society vary according to many factors.

The alternative to land disposal that deep-sea disposal represents, and the associated risks, are not widely agreed upon between the industry, academics and civil society. Perceptions may vary considerably and points of divergence need to be identified to assess how this disposal method contributes to the overall discussion of waste management. Some believe that even though the disposal of waste offshore may have a substantial impact on marine ecosystems, it may prove to be the best of a damaging set of options (Angel *et al.*, 1997; Thiel *et al.*, 1997).

CANMET has recently carried out some independent research on the marine disposal of mine waste, in both shallow and deep water, concentrated on historic tailings disposal sites on the east coast of Canada. A series of reports and papers will be released in the near future though one is already available to the general public (Blanchard *et al.*, 2001).

4.1 The Marine Environment

The implications of marine disposal of mine waste depend on the discharge depth. Different layers can be identified in the ocean. The depth of these layers undergoes seasonal changes, which can be predicted and monitored. The layers are as follows (Jones and Jones, 2001):

- The **surface mixed layer** is the upper layer in the ocean that is kept well mixed by the turbulent action of wind and waves. As a result, the surface layer tends to be of uniform temperature, density and salinity. The bottom of the surface mixed layer is generally marked by an abrupt density discontinuity.

- The **euphotic zone** is defined as the depth reached by only 1% of the photosynthetically-active light transmitted from surface. The ocean's highest biological productivity occurs in this zone, where light allows for plant photosynthesis to occur.
- **Upwelling** is a natural phenomenon found in few parts of the world and occurs wherever deeper (cooler) water is transported to the surface. Upwelling can be a regional phenomenon, where submarine currents meet land masses, or localised, caused by wind shear effects, where wind-driven surface water is replaced by deeper water.

4.2 Shoreline and Surface Water Disposal

Shoreline or surface water disposal involves waste rock and tailings discharge directly onto the shore, or into shallow water (i.e. at depths less than 20–30 m deep). For example, at the Misima mine in PNG, 50 million tonnes of soft waste rock (soil and incompetent rock) were disposed of on the shoreline (Jones and Jones, 2001). Tailings have been discharged at varying shallow depths from shore, from ships or piped to different distances from the shore. At the Atlas Copper Mine in the Philippines, tailings were piped 200 m from shore and released at 10 m depth. When tailings are discharged to a river, they may also end up being discharged to the marine environment, as discussed in Section 3 on Riverine Disposal

The potential environmental impacts from shoreline and shallow water waste disposal are generally severe. Waste rock or tailings can accumulate on shore, as they did at Marcopper. During the marine disposal phase, "*a tailing causeway started to build up and was progressively extended into the embayment. By 1986 [when marine disposal ceased], the causeway extended some 4.5 km offshore*" (Jones and Jones, 2001). Surface turbidity increases to levels which can affect photosynthesis, and intertidal and shallow benthic flora and fauna are smothered. If toxic metals and process chemicals are present in the tailings, and bio-available, they can enter the marine food chain which may be harvested by humans. This form of marine disposal may affect marine livelihoods and could create health problems for local coastal communities, though there is little documented information available. These impacts are basically similar to coastal impacts from riverine disposal discussed in Section 3 on Riverine Disposal. Mines where shoreline and surface water marine disposal was used are listed in Table A4.

Table A4. Shoreline and surface water marine tailings disposal sites

Mine	Operator	Location	Status	Rate (tonnes/day)	Depth (m)	Setting and deposition depth
Marcopper (Copper)	Placer Dome	Marinduque Island, The Philippines	Closed 1975–1986	113 Mt total	NA	Shallow embayment
Boulby Potash	Cleveland Potash	UK	Operational 1972–	600	14	North Sea
Atlas Copper (Copper)	Atlas Consolidated Mining & Development Corporation	Cebu Island The Philippines	Closed 1971–1974	100,000	10	Island Strait >500m
Jordan River (Copper)	Jordan River Mines Ltd.	Vancouver Island Canada	Closed 1962–1974	~450	12	Juan de Fuca Strait
Nome (Gold)	West Gold Alaska	Alaska USA	Closed 1985–1990	40,000	Behind dredge	– 4.8–21 m
Toquepola and Cuajone (Copper)	Southern Peru Ltd Asarco	Peru	Retro-fitting feasibility considered early 1990's	100,000	20	Shallow coastal Shelf
Petaquilla (Copper, gold)	Irian Resources, Teck Corporation and Inmet Mining Corporation	Panama	Feasibility stage	100,000 20 yr mine life	NA	Caribbean Sea

*Projects that are proposed, under investigation or investigated but not implemented are shaded
Source: Jones and Jones (2001)

4.3 Shallow Water Disposal

Disposal of waste rock or tailings below the euphotic zone, so that they deposit and remain on the sea floor can limit the impacts. Shallow water disposal of tailings involves discharge to a selected underwater target area, from a submerged pipeline below the euphotic zone into fjords, fjord-like sea channels and coastal seas at depths approximately between thirty and several hundred metres

This method was used at the Island Copper Mine in Canada and used for 25 years. Tailings were deposited in a sheltered fjord and remained almost entirely in the intended deposition area. Although the tailings mostly remained on the sea floor, some re-suspension of tailings did occur due to: "*A high-density tidal current on occasions [..] descends to the seabed resuspending tailings and upwelling them to surface*" (Ellis *et al*., 1995). According to the Mineral Policy Centre, approximately 0.3%, or over one million tonnes of tailings, were resuspended and spilled into an adjoining fjord (Moody, 2001) though the company puts the figure at 100-200 tonnes. Mines where shallow water marine disposal was used are listed in Table A5.

4.4 Deep Sea Tailings Disposal

Another way of attempting to minimise the risk to tailings rising to the surface of the water column is by depositing the tailings on the sea floor at great depths. Density differences in the ocean water column cause stratification, which is effective in trapping the tailing solids at depth. DSTD is defined as the discharge of a tailing slurry from a submerged outfall with ultimate deposition at 1000 m or deeper (Jones and Jones, 2001). Typical outfall depths for DSTS systems range from 100 to over 300 m. Table A6 lists DSTD sites.

The criteria for identifying potential DSTD sites includes: accessibility to the coast; suitable bathymetry and physical oceanography (submarine slopes steep enough to carry tailings to a deep target deposition area and water conditions allowing tailings to form a density current); and a secure outfall site (Ellis *et al*., 1995). Suitable sites are restricted to some oceanic islands and archipelagos where very deep water occurs close to shore. These criteria are met at many potential mine sites in Indonesia, the Philippines and Papua New Guinea. Several DSTD mining projects exist or are being considered in this region.

Figure A1 shows the main components of a deep sea tailings disposal system.

Table A5. Shallow water marine tailings disposal sites

Mine	Operator	Location	Status/ duration of marine disposal	Rate (tonnes per day)	Depth (m)	Setting and deposition depth
Minahasa (Gold)	Newmont	North Sulawesi Indonesia	Operational 1996–	3000	82	Coastal shelf >160 m
Huasco Pelletising Plant (iron)	Compania Minera Del Pacifico	Chile	Operational 1994–	3000	NA	Chapaco Bay
Rana Gruber (iron)	Rana Gruber SA	Norway	Operational 1964–	1600	15 then 50	Ranafjorden 700 m
Island Copper	BHP Minerals	British Colombia Canada	Closed 1971–1995	33,000–55,000	30-50	Silled fjord >100 m
Kitsault Molybdenum	Amax	British Colombia Canada	Closed 1981–1982	12,000	50	Silled fjord >350 m
Black Angel Lead/zinc	Cominco	Greenland	Closed 1972–1991	1650	30	Shallow fjord ~80 m
Titania Ilmenite	Titania AS	Jossingfjord Norway	Operating 1960–1980	~6000	100	Fjord >100 m
Sydvaranger Iron	Sydvaranger ASA	Bokfjorden Norway	Closed 1975–1998	4600-6000	22	Fjord 220 m
Tampakan Copper/gold	Western Mining Corporation	Southern Mindanao Philippines	Preliminary planning stage	NA	NA	Deep coastal embayment
Kensington Gold	Coeur Alaska Inc	Alaska US	Exploration prospect	NA	NA	Fjord

*Projects that are proposed, under investigation or investigated but not implemented are shaded
Source: Jones and Jones (2001).

Table A6. Deep sea tailings disposal sites

Mine	Operator	Location	Status	Rate (tonnes/day)	Depth (m)	Setting & deposition depth
Cayeli Bakir Copper/zinc/lead	Inmet Mining	Turkey	Operational 1994-	Initially 12,000	390	Black Sea >2,000 m
Misima Gold/silver	Misima Mines Placer Dome	PNG	Operational 1989-	15,000-22,000	112	Solomon Sea 1,500 m
Lihir (Gold)	Lihir Management Company, Rio Tinto	PNG	Operational 1996-	8,000	128	Open Ocean >2,000 m
Marseilles Aluminium	Pechiney (Plant 1) - (Plant 2)	Marseilles France	Operating 1967-	4,000 combined	320 & 330	Submarine canyon 1200 m
Batu Hijau Copper/Gold	Newmont	Sumbawa Island Indonesia	Operational Sept 1999-	120,000	108	Open ocean >4,000 m
Simberi (Gold)	Nord Australex	PNG	Permitted	3,000	115	Oceanic island >2,000 m
Ramu Nickel (Nickel/cobalt)	Highlands Pacific	PNG	Feasibility stage	14000	150	Submarine canyon >2000 m
Awak Mas (Gold)	Masmindo Mining	South Sulawesi, Indonesia	Feasibility stage	NA	NA	Gulf (Teluk Bone) >2,000 m
Gag Island (Nickel/cobalt	PT Gag Nikel BHP Minerals	Gag Island Indonesia	Feasibility stage	Under development	~150	Oceanic island >1,600 m
Toka Tindung (Gold)	Aurora	North Sulawasi Indonesia	Permitted	NA	150	Oceanic Island
Weda Bay (Nickel/cobalt)	Weda Bay Minerals	Halmahera Island, Indonesi	Feasibility stage	NA	NA	Oceanic Island
Koniambo (Nickel/cobalt	Falconbridge	New Caledonia	Feasibility stage	NA	Nominal 15	Oceanic Island
Nakety (Nickel/cobalt)	Argosy Minerals Inc	New Caledonia	Feasibility stage	NA	NA	Oceanic Island
Moneo (Nickel/cobalt)	Moneo Metals Ltd	New Caledonia	Feasibility stage	NA	Nominal 15	Oceanic Island

*Projects that are proposed, under investigation or investigated but not implemented are shaded. Source: Jones and Jones (2001

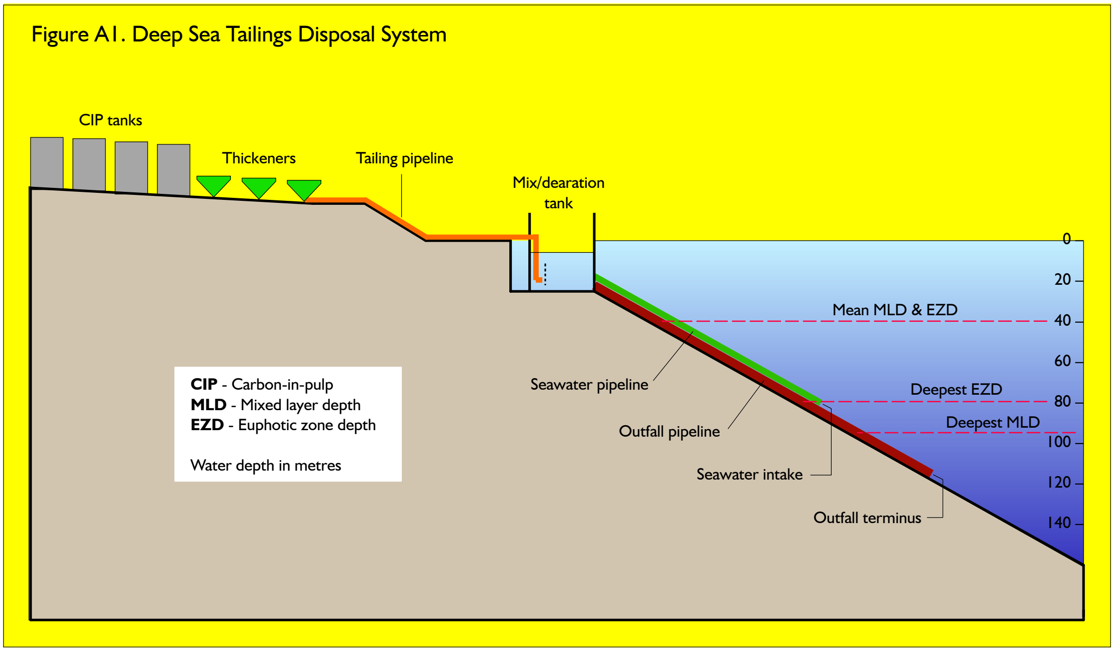

Figure A1. Deep sea tailings disposal system (from Jones and Jones, 2001)

4.5 *Engineering Considerations*

Shallow water and deep sea tailings disposal engineering involves many components. Air bubbles must be removed from the slurry to prevent the tailings from being entrained to the water surface. For example, at the Atlas Copper Mine in the Philippines, air was not removed from the tailings prior to discharge. "*As a result, the tailings formed a noticeable surface plume. However, the majority of the tailing solids were transported down [..] into water depths exceeding 300m.*" (Jones and Jones, 2001). De-aeration can take place at the concentration plant, with a choke station at the coast like at the Minahasa Raya site, or more frequently by a de-aeration tank on the coast, like at the Misima site. Prior to de-aeration, or transportation to shore via pipeline, tailings are sometimes thickened to recycle water and process chemicals. For example, at Misima freshwater is at a premium and thickening is used. In some cases, tailings are also treated to remove process chemicals.

Before being discharged, tailings are sometimes mixed with seawater. Seawater with a suitable density and temperature is extracted from an appropriate depth into a mixing tank. Seawater has a coagulating action on the tailings slurry, and solids tend to flocculate in receiving marine environments (Poling, 1995). The mixing tank also provides a dilution factor and acts as a buffering zone to handle increases in production. These tanks are not used in all DSTD systems. For example, no such tank was used at the Minahasa Raya site (Jones and Jones, 2001).

The entry point of the pipe into the sea and its location is important to maintain pipeline integrity and avoid breakage problems. Sheltered sites are preferable and adequate pipe material must be chosen. For example, at two sites, Jordan River and Batu Hijau, pipeline breaks have occurred. Leaks have also been detected (Minahasa). Typhoons and other storm events can increase the risk of pipe rupture. For example, at the Atlas Copper Mine site the pipeline was wiped out during a typhoon.

The underwater outfall of the pipe must also be designed to avoid pipe blockage or breakage. This can occur if the tailings flow is not at a steep enough exiting angle, the level of which is determined by the physical characteristics of the slurry but has been generalised at ~12% (Jones and Jones, 2001). For example, at the Minahasa Raya site the tailing pipe discharges onto a 2° slope at ~80 m depth. Tailings fail to flow to deeper areas and have accumulated at the outfall site. As a result, blockage of the pipeline has occurred. Experience from other DSTD sites shows that seabed slopes of at least 12° are required to avoid the risk of significant build-up of tailing downslope of the outfall (Jones and Jones, 2001). To avoid blockage, the rate of discharge must also be controlled in accordance with the pipe's capacity and regular maintenance of the pipeline has to be undertaken. At the Lihir mine, the pipeline was placed through a coral reef lined with steel casing to ensure it's long-term integrity on the steep submarine slope.

The pipeline releases tailings as a high velocity jet that slows at a short distance from the pipeline "*due to entrainment of seawater and frictional losses*" (Jones and Jones, 2001). The mixture continues to descend along the sea floor as a coherent density current. Sea floor currents have to be taken into account as they might affect the flow of the density current. The tailings eventually deposit on the sea floor according to size, with the coarser grains depositing first. The tailings density current flows like a meandering river over the seabed. As a result there is a dynamic system of channels and levees, which means some erosion and resettling of deposited particles.

As the tailings current flows down the sea floor, it may pass through density discontinuities and plumes of the finer sediments may form and disperse away from the density current forming subsurface plumes. This can occur at several different depths as the tailings current continues to flow down the sea floor slope to a final deposition area (Jones and Jones, 2001). Plumes are 'clouds' of tailings liquor, seawater and very fine suspended sediment particles. They contain residual process chemicals, and possibly metal or other element concentrations. Although they are dilute compared to the tailings discharged, they have higher turbidity than surrounding water. Plumes remain at specific depths because of seawater stratification, it is assumed that they slowly flocculate and settle. They become more dilute with increasing distance from the area where they form, ocean currents and turbulence can disperse plumes.

4.6 Risks and Concerns

The smothering of benthic fauna at the ultimate deposition area and along the route of the tailings flow occurs when the deposition rate is greater than the ability of slow moving organisms to move away. At depth, the extent of this impact is difficult to predict because little is known about deep sea benthic organisms and deep sea ecosystems. Possible interactions and dependence between benthic fauna and surface fauna would imply risks to marine species throughout different ocean depths. The types and likelihood of frequent interactions are considered minimal by the industry.

Annual biodiversity surveys of deposited tailings at Island Copper have demonstrated that they can be re-colonised rapidly, within several years of deposits stabilising (Ellis and Robertson, 1999). Studies based on shallow marine ecosystems have demonstrated that primary opportunists settle first, and within 1–2 years form a sustaining ecological succession). Monitoring at the Misima site has also shown that re-colonisation of sediments by bacteria and meiobenthos was observed at over 1,000 m after 5 years of deposition. Benthic species that re-colonise tailings are observed to be different from original species, both in number and types. This can change predation and competition patterns, leading to shifts in marine species community structures (Moody, 2001).

The risk for potential biological impacts from plumes depends in part on levels of turbidity and toxicity, natural suspended solid levels, the depth at which the plumes form, and the sensitivity of marine organisms to these disturbances. Species that rely on bioluminescence could be vulnerable to changes in water turbidity. Depending on the levels of metals or other potentially toxic elements in plumes, bio-accumulation are risks at some sites. Some studies have demonstrated that certain fish species show preferences for feeding at the edge of subsurface plumes (Jones and Jones, 2001; Garnett and Ellis, 1995). The extent to which this is an issue is unknown because of the difficulty of making accurate field measurements.

Leaching of toxic elements or metals from tailings in seawater has been cited as a potential risk by marine disposal critics. In theory, leaching may occur directly into the water column or in the pore water of the tailings and diffuse into the water column. Diffusion of pore water could accelerate as tailings get compacted by fresh tailings deposition (Moody, 2001). One of the criteria for shallow water and deep sea tailings disposal is that the "*chemistry of the [mine waste] must be such that there is minimal risk of toxin solubilisation, leaching to water column, and entry to biological cycles*" (Ellis *et al*., 1995). Test work is required to characterise the toxicity of potential contaminants in the tailings and pore water within the deposited tailings (Jones and Jones, 2001). Treating and detoxifying tailings prior to discharge can greatly increase the chemical stability of the tailings in seawater.

At some DSTD sites (such as Lihir and Misima), a 'mixing zone' at the pipe outfall is allowed for dilution of tailings. Compliance with regulatory standards is measured beyond this zone. Current best practice for deep sea tailings disposal states that after allowance for dilution with seawater in a mixing zone "*the concentrations of potential contaminants should be non-toxic to marine life and in compliance with appropriate water quality standards*" (Jones and Jones 2001).

If existing or potential fisheries are affected, these can lead to socio-economic impacts. These have been reported in some literature (such as Moody, 2001) though fishery losses clearly attributable to shallow water and deep sea tailings disposal have not been clearly documented. Prior to selecting a disposal site, current best practice recommends that existing and potential fisheries at the selected site and predicted final deposition area be assessed for minimal conflict.[10] Part of judging this risk includes predicting where the density current will flow, where subsurface plumes will form and their level of turbidity, the leaching and bio-availability potential, and ensuring that there will be no impacts in the euphotic zone.

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[10] As outlined by Jones and Jones (2001)

Shallow water and deep sea tailings disposal facilities are designed to have little impact on shallow marine waters, coral reefs and shallow water fisheries. On the other hand, design, construction and operational problems are difficult to contain, remediate, and even detect. Some examples include; blockage of seawater intake by marine organisms, air entering the tailings pipe (Cayeli Bakir), submarine landslides damaging the tailings pipe (Misima). Unforeseen occurrences and operational failures could impact shallow coastal waters, reefs and fisheries, especially when important amounts of tailings are being disposed of. Emergency response mechanisms are important in light of the difficulty resulting from the underwater depths involved.

Accurate and detailed prediction and risk assessment are necessary to address these potential risks. Baseline data and on-going monitoring is a key part of this process. Water and sediment quality has to be monitored "*including water column profiles and tailing deposition, impacts on fish populations, metal uptake in fish and impacts of smothering benthos*" (Jones and Jones, 2001).

4.7 *Shallow Water and Deep Sea Tailings Disposal* versus *Land disposal*

The environmental and socio-economic risks associated to land disposal are well known. In some areas, conditions can significantly threaten the physical and chemical stability of land disposal facilities. The shallow water and deep sea tailings disposal alternative is considered a viable option when the right geographic conditions exist and "*where there are significant potential land use conflicts and/or where there are potentially severe consequences associated with the possible [physical or chemical] failure of on-land tailing storage structures*" (Jones and Jones, 2001). Best practice requires that at least one land disposal alternative be considered during the feasibility phase.

Considering long-term liability issues associated with land disposal, shallow water and deep sea tailings disposal options have the potential to be less costly. Acid generation treatment and tailings impoundment stewardship are potentially very costly concerns, which are not an issue at shallow water and deep sea disposal sites.

Although the risks associated with land disposal are well known, there is no consensus about the risks associated with shallow water and deep sea tailings disposal between the industry, academics and civil society. The number of shallow water and deep sea disposal case studies is limited and the time frame is such that long term validation is not yet possible. The most extensive data available is for Island Copper where a detailed environmental monitoring programme was carried out for a period of more than 25 years. This concern prompted a call for an international ban on STD and demands that mining companies accept liability for impacts, at an international conference on Submarine Tailings Disposal held in Indonesia in April 2001.[11]

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[11] STD is referred to as ocean dumping of mine waste in this case

4.8 Legislation

Marine disposal of mining waste has been permitted at different mine sites around the world. Few countries directly address shallow water or deep sea tailings disposal in their environmental or mining legislation. In many countries, policy on DSTD is arguably not explicit. Whether an activity is permitted within the law depends on a complex array of factors, including whether or not this may be considered as an option by the regulator, as well as how the decision-making processes operate (including the level of non-government participation) (Box A6). The clarity of the law on this topic also depends on the availability of marine disposal sites and alternatives (and thus the extent to which it has been implemented *in practice*). In South Pacific Asia, deep sea tailings disposal is being considered at more sites than any other region, mainly in Indonesia, Papua New Guinea and the Philippines.

Box A6. Examples of national policy regarding submarine tailings disposal

In **Indonesia**, no regulations specifically apply to the disposal of mine waste. There are water quality standards for industrial activities, although this does not include mining. Discharge standards for the mining industry may, however, be specified by the relevant Minister. Failing this, the Govenor of the Province in which the project is proposed may use the general water quality standards in determining whether a project may proceed. Environmental impact assessment (EIA) is required for mine projects. Several proposals involving marine tailing disposal have been though the EIA process and approved.

In **Papua New Guinea**, the government allows submarine tailings disposal to be considered alongside other forms of tailings management. The Draft Environmental Code of Practice for the Mining Industry in Papua New Guinea does make reference to submarine tailings disposal as a waste disposal option. There is a requirement for environmental impact assessment of mine projects and a permit under the Water Resources Act, 1982. Four projects with DSTD have been approved: Misima, Lihir, Simberi Gold Project and Ramu Nickel Project.

In the **Philippines**, specific government policy regarding deep sea tailings disposal states that this is permitted "*only when other tailings disposal and management options are not environmentally, socially, technically and economically feasible or when deep sea tailings placement systems exhibited the least environmental and social risk*" (DNER Memorandum Order No. 99, Section 19). An Annex to the Philippine Mining Act of 1995 provides for submarine tailings disposal to be considered as an option. There are, however, no examples of operating mines using submarine tailings disposal.

In the **US**, wastewater effluent standards for suspended solids, managed by the USEPA, preclude DSTD. The implementation of these regulations has, however, proved that exemptions are possible where there are no viable alternatives. Two examples, both situated in Alaska, are the A.J. Mine Gold Project near Juneau and the Quartz Hill Molybdenum Project. Neither of these projects became operational.

Box A6 – *contd.*

In **Canada**, the law does not prevent DSTD being proposed, and considered by the authority. The discharge standards in the Metal Mining Liquid Effluent Regulations (MMLER) make it extremely difficult to obtain a permit for this waste disposal option. On the other hand, as with the US, exemptions have been made. The Island Copper Mine and Kitsault Molybdenum Mine (both of which had operated before MMLER). DSTD was considered in 1997 as an option for the Voisey's Bay Nickel Project.

In **Australia**, there is no law that specifically prevents submarine tailing disposal from being considered as an option, if the project conforms with the Australian and New Zealand Environment and Conservation Council's Interim Ocean Disposal Guidelines (December, 1998). There are, however, no cases of proposals (except for the Pasminco Hobart smelter, which was regulated under the provisions of the London Convention: Box A7). The Australian Best Practice Environmental Management in Mining Modules do not include marine tailing placement.

Source: Jones and Jones (2001)

Some international standards and programmes apply to marine disposal of mine wastes, including The London Convention, The Law of the Sea Convention and the Global Programme of Action (see Boxes A7–A9). The application of these instruments to mine wastes is complex, and therefore subject to uncertainty. It has been suggested that DSTD does not contravene the London Convention because it does not apply to pipeline discharges and contains no specific reference to tailing or mine waste (Jones and Jones, 2001). Even where dumping of mine wastes from ships is involved, the applicability of the London Convention is debatable. In principle, The Law of the Sea Convention should strengthen participation in the London Convention and its Protocol, but clearly this has not been the case.

In spite of the apparent lack of preclusion of DSTD in international laws, opinions are divergent on the interpretation. At a recent conference on marine disposal in Manado, Indonesia, it was maintained that "*Submarine Tailings Disposal is illegal in Canada and the USA, has never been proposed in Australia, and violates the spirit of international covenants that protect the marine environment*" (Manado Declaration on Submarine Tailings Disposal).

The World Bank maintains that "*marine discharges of tailings must not have a significant adverse effect on coastal resources*" (World Bank Environment, Health and Safety Guidelines, as cited in Jones and Jones, 2001).

Box A7. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972.

The London Convention entered into force in 1975 and by the end of 2001 had been ratified by 78 countries. It regulates the deliberate disposal of wastes at sea by dumping or incineration. This includes territorial waters, but not inland waters. 'Dumping' is defined as disposal occurring from vessels, aircraft, platforms or other man-made structures at sea. Thus, mine wastes are included if they are discharged from a ship, but not from a pipe or fixed structure connected to solid ground.

The Convention bans the disposal of certain materials, including industrial wastes, but this excludes "uncontaminated inert geological materials the chemical constituents of which are unlikely to be released into the marine environment" (Annex I, paragraph 11 e). Such material is subject to a permission procedure. In establishing criteria governing the issue of permits, parties must consider a set of provisions, including the characteristics and composition of the matter, characteristics of the dumping sites, and the method of deposit (Annex III).

Following calls to extend participation in the Convention and improve its environmental standards, a Protocol to the Convention was signed in 1996. The description of what is meant by 'dumping' remains the same in both instruments. A key difference between them is that whereas the Convention itself lists material that is explicitly precluded from dumping, the Protocol does the reverse; stipulating that no material should be dumped except for that which occurs on a list (Annex 1). Inert, inorganic geological is included in the Annex 1, but this material cannot be dumped without a permit. The permit must follow certain criteria (Annex 2). Specific guidelines for the interpretation of the Protocol regarding inert, inorganic geological material were adopted in 2000. The designated authority must specify the basis upon which material is specified as inert and geological. Applicants for permits to deposit this material must demonstrate that they have considered alternative means of disposal or use, otherwise the permitting authority must refuse. The guidelines also cover dump-site selection and the assessment of potential effects.

Although 16 countries had ratified the Protocol by the end of 1996, this number falls short of the 26 required for entry into force. Thus, for the time being, the 1972 London Convention remains the instrument in force for the majority of its signatories.

Box A8. The 1982 United Nations Convention on the Law of the Sea (UNCLOS)

UNCLOS governs all aspects of ocean space, including delineation. It entered into force in 1982 and as of November 2001, had been ratified by 137 States. Part XII of the Convention (articles 192 - 237) addresses the management of the marine environment. Parties are obliged to prevent, reduce and control pollution from land-based sources and pollution by dumping. Pollution is comprehensively defined and dumping is defined in a similar manner to that of the London Convention, namely any deliberate disposal of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea. Numerous articles apply in principle to marine disposal of mine wastes, although Number 207 is one of the most specific.

1. States shall adopt laws and regulations to prevent, reduce and control pollution of the marine environment from land-based sources, including rivers, estuaries, pipelines and outfall structures, taking into account internationally agreed rules, standards and recommended practices and procedures.
2. States shall take other measures as may be necessary to prevent, reduce and control such pollution.

All States parties to UNCLOS are legally bound to adopt laws and regulations that are no less effective than the global rules and standards (Article 210), which are considered to be those of the London Convention 1972. They will also be obliged to enforce such laws and regulations in accordance with article 216 of UNCLOS. This is significant given that view of the fact that as many as 69 out of 130 States Parties (as of 5 January 1999) are not a Contracting Party to the London Convention 1972.

Box A9. The Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities.

The Global Programme of Action (GPA) for the Protection of the Marine Environment from Land-Based Activities, was adopted by 108 governments following an international conference on this topic in 1995. This acts as a reference point for governments and regional authorities seeking guidance in devising and implementing sustained action to prevent, reduce, control and/or eliminate marine degradation from land-based activities. The GPA is co-ordinated by UNEP, although implementation remains primarily the task of participating Governments. The programme is oriented around seven groups of pollution sources. These include ‘heavy metals’, and ‘physical alterations’ but make no specific mention on mine wastes.

4.9 End Use

The intended end use of mine waste facilities should also be taken into account when assessing waste disposal options. Considering possible end use from an early stage of mine planning activity could influence waste management practices and the level of potential environmental and social impacts. An important aspect of mine planning is the rehabilitation of waste disposal sites to a stable and productive post-mining landform, which is suitable and/or acceptable to the community. The essential goal of site rehabilitation is to return all affected areas, as near as possible, to their optimum environmental, social and economic value. This does not always involve returning a site to its original state or use. The main aims of site rehabilitation are to reduce the risk to a level that does not pose a significant environmental or human health problem, to restore the land and landscape, to improve the aesthetics of the area and to prevent further degradation. Through consultation with relevant interest groups, including the regulatory authority, traditional owners and private owners, the mine operator can establish the required future land use for the different waste disposal facilities. This should be done as a multi-stakeholder consultation process.

Unfortunately, very few metal mines have been developed in the past where the end use of the site was a significant consideration. It is expected that this approach will change as mining companies encompass the concept of sustainable development. The closure plans for the Waihi gold mine, New Zealand, are a good example of pre-planned end use of the facilities. The open pit, located in the middle of the town of Waihi will become a recreational lake, while the tailings disposal facility located about 3 km away will be a combination of wetlands, grassed areas and ponds (Slight, 2000). Another example of preplanning for closure was Kennecott Minerals' Flambeau mine in Wisconsin, US where the mine waste was backfilled into the pit and the site was rehabilitated as a park and wetland area, with hiking trails and wild life observations points. This was done as a condition of approval for the mine after an extended permitting process.

In most cases in the past the final end use for the waste disposal facilities have not been clearly established until the economic reserves were nearly depleted and the closure of the mine was being planned. This can restrict the options and increase closure costs, even though the end result may be seen as a success. For new mines, a closure plan must be developed as part of the environmental impact assessment. Planning and operating for closure, with that plan in mind, should then be the philosophy (see Appendix B). The closure plan is updated on a regular basis during operations so that a final end use of the site (including the large volume waste) is established.

Making decisions during the design phase about the end use of a mine site can be easier when the mine life is limited. For example, new aggregate quarries in highly populated areas may be designed so that a golf course can be developed on the site after mining. This establishes new challenges to the mine planner, as the disposal of waste, etc. must be planned to fit with the final site development plan without re-handling.

While an end use may be identified during planning for mines that have a longer life, it will almost always be necessary to review these decisions as mine life progresses. Changes may occur in the either the quantity and type of waste or the receiving environment. For example, increases in the local population, that occur during the mine life, may create new end use opportunities for the area and infrastructures developed by the mining company may create economic opportunities that did not previously exist. Technological changes, changing preferences of the local communities and regulators are some of the issues to be taken into account in the overall land use planning.

In many parts of the world, the more common end use for waste disposal facilities is forest, natural scrub, and grazing or arable land. At the Tara mine in Ireland a number of trials were carried out into grazing domestic livestock on sections of a rehabilitated tailings disposal facility. These showed that, if managed correctly, this was an acceptable end use and the lambs used in the study were suitable for human consumption.

An important potential end use of mine pits is as landfills for municipal and other non-hazardous waste. This use is highly dependent on site-specific conditions such as the potential for groundwater contamination, location of the pit with respect to where the waste is being produced, etc. A plan has been developed to dispose of municipal waste from Los Angeles in the Mesquite pit in South Eastern California. It is proposed that the waste be transported from Los Angeles to the mine by train.

Assessments of waste disposal options should include alternative end uses for the waste itself. In some cases the waste may be suitable as aggregates for road construction and building materials. However, the quantity of waste produced is often far in excess of the demand or the mine is not located near a centre where such materials are required.

Decisions on the end use of waste disposal facilities, or the waste, must evaluate health and safety implications and environmental risks. These may be in the form of physical danger, heavy metals in soils and/or water or plant uptake of metals. It may also include direct human contact with contaminated areas.

Conclusions and Recommendations

See the Main Report of *Mining for the Future* for general discussion and recommendations.

References

See separate References for the Main Report and Appendices.