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Paste and thickened tailings — friend against acid and metalliferous drainage?

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Abstract

Tailings management has been a rapidly growing and demanding challenge across the global mining industry over the past century, primarily due to growing metals demand (and consequently production), declining ore grades (including refractory mineralogy issues), and increasingly stringent environmental and technical requirements. The typical approach historically has been to build engineered storage structures, involving valley fill walls or ring dykes, with the tailings delivered to the tailings storage facility (TSF) via a slurry pipeline. Conventional embankments, however, can fail under a variety of mechanisms and cause catastrophic environmental and public health impacts — the most recent event being the red mud dam failure in Hungary. Another major environmental issue associated with tailings (and waste rock) is the generation of acid and metalliferous drainage or AMD (also commonly known as acid mine drainage). The cause of AMD is the exposure of sulphidic minerals, such as pyrite and pyrrhotite, in mine wastes to water and oxygen, leading to oxidation and the release of sulphuric acid. This in turn dissolves a strong cocktail of heavy metals and if allowed to reach the environment, AMD can cause extreme impacts on biodiversity, water quality, ecosystem health and public amenity. If left unaddressed, AMD pollution can continue for hundreds or potentially even thousands of years. Over recent decades, major advances in thickening technology have enabled the development of paste and thickened tailings (P&TT) to be adopted as a realistic and economic alternative to conventional tailings dams. The primary driver of P&TT technology is the non-Newtonian fluid behaviour of the solid suspension of water and tailings. Given that one of the primary drivers of AMD is excess water flowing through the mine waste — can the relatively low moisture content and rheological characteristics of P&TT provide a natural defence against AMD generation? This is a fundamentally critical question and deserves thorough assessment and consideration. At present there appears to have been virtually no research on linking AMD issues to P&TT management, although it is understood that there appears to be no indications of AMD problems at existing P&TT operations. This paper will therefore review the basics and the scale of AMD problems around the world, present the essential rheological characteristics of paste and thickened tailings and then critically examine the potential for AMD associated with P&TT management. It then attempts to answer that critical question: can the P&TT provide a natural defence against AMD problems? The paper is therefore a timely and perhaps unique view of another potential advantage in P&TT which is yet to be well understood and receive due recognition.

1 Introduction

> *"... when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away." (Agricola, 1556)*

This famous quote from Georgius Agricola, initially a doctor and later a miner from Saxony in eastern Germany and widely recognised as one of the founders of the modern mining industry, is stark recognition of AMD. In other words, the acidic, metal-rich pollution which can often accompany mines all over the world has long been recognised as a major impact — the principal difference between Agricola's era and now is the sheer massive and global scale of mine waste problems and associated AMD issues as well as a raft of environmental regulations relating to managing mine wastes.

All mining projects produce two principal forms of waste, tailings and waste rock (or overburden in the coal sector), and both types can present major AMD risks. Due to growing metal demands and declining ore grades, and especially the expansion of open cut mining, the mass of mine waste produced annually by the global mining industry is of the order of tens of billion tonnes (or more) and growing rapidly every year.

This mass of mine waste presents major challenges to assess and manage to prevent unacceptable environmental and human health impacts, especially as regulatory requirements and community expectations continue to improve. Typically, waste rock is placed in large heaps or dumps, while tailings are contained in valley fill or ring dyke structures and deposited using a slurry pipeline. Either approach presents various risks, depending on complex factors (especially climate and geographic issues). Some examples of TSF disasters include Bafokeng (1974, platinum), Los Frailes (1998, base metals), Baia Mare (2000, gold) or most recently Kolontár (2010, red mud) — all having major environmental impacts and/or loss of life. A widely cited quote, attributed to the US Environmental Protection Agency from 1987, states that:

> *"problems related to mining waste may be rated as second only to global warming and stratospheric ozone depletion in terms of ecological risk. The release to the environment of mining waste can result in profound, generally irreversible destruction of ecosystems" (The primary US EPA source/report for this quote is unknown; it is cited by EEB, 2000)*

In a similar vein, the International Network for Acid Prevention (INAP) states as the first line on their website that "acid drainage is one of the most serious and potentially enduring environmental problems for the mining industry" (see www.inap.com.au).

Over recent decades, major advances in thickening technology have enabled the development of P&TT to be adopted as a realistic and economic alternative to conventional tailings disposal. By 2006, more than 25 mining operations had implemented P&TT disposal. The primary driver of P&TT technology is the non-Newtonian fluid behaviour of the solid suspension of water and tailings. Given that one of the primary drivers of AMD is excess water flowing through the mine waste — can the relatively low moisture content and rheological characteristics of P&TT provide a natural defence against AMD generation? This is a fundamentally critical question and deserves thorough assessment and consideration.

At present there appears to have been very limited research assessing AMD issues associated with P&TT management, although it is understood that there appears to be no major AMD problems at existing P&TT operations. This paper will therefore review the basics and the scale of AMD problems around the world, present the essential rheological characteristics of paste and thickened tailings and then critically examine the potential for AMD associated with P&TT management. It then attempts to answer that critical question: can the P&TT provide a natural defence against AMD problems? The paper first reviews the nature of acid and metalliferous drainage, briefly examines the extent of global mine waste generation, then covers common technical approaches to assessing and managing AMD risks in modern mining projects, and finally compares the characteristics of paste and thickened tailings and contrasts this with AMD management. The paper is therefore a timely and perhaps unique view of another potential advantage in P&TT which is yet to be well understood and receive due recognition.

2 Mine wastes and AMD

Mining generates vast quantities of solid wastes, predominantly as tailings (residual solids after metal or mineral extraction) or waste rock (material with no economic metals or minerals). Given the wide variety of commodities mined, different ore types, geologic and geographical settings of mines all over the world, the geochemical characteristics of ore, tailings and waste rock and their interaction with the local environment varies considerably. The fundamental starting points under any scenario are the sulphide content and mineralogy of mine wastes and the availability of water and oxygen. This section provides a brief of the primary mechanisms of acid and metalliferous drainage, with more detailed found in various reports and papers (e.g. Langmuir, 1997; Parker and Robertson, 1999; Blowes et al., 2003; Taylor and Pape, 2007; Lottermoser, 2007; Spitz and Trudinger, 2008). Other common terms include acid mine drainage or acid rock drainage (ARD) (AMD is very similar to acid sulphate soils common in estuarine or wetland settings).

The overall process of AMD involves exposure of sulphidic minerals to water and oxygen, sulphide oxidation, leaching and escape into the environment, mainly through surface water or groundwater pathways. The dominant sulphide minerals involved are pyrite (FeS_2) and pyrrhotite ($Fe_{1-x}S$), though others can play a minor role. The geochemistry is considered to be a three-stage process, the first being primary sulphide oxidation (Equation (1)), followed by oxidation of ferrous to ferric iron (Fe^{2+} to Fe^{3+}) (Equation (2)), and finally the ferric iron forming ferrihydrite (Equation (3a)) or further enhancing oxidation of sulphides (Equation (3b)).

These steps can be simply described as (Lottermoser, 2007):

Primary oxidation:

$$2\,FeS_{2(s)} + 7\,O_2 + 2\,H_2O \rightarrow 2\,Fe^{2+} + 4\,SO_4^{2-} + 4H^+ \tag{1}$$

Ferrous oxidation:

$$4\,Fe^{2+} + O_2 + 4\,H^+ \rightarrow 4\,Fe^{3+} + 2\,H_2O \tag{2}$$

Ferrihydrite formation:

$$Fe^{3+} + 3\,H_2O \rightarrow 4\,Fe(OH)_3 + 3\,H^+ \tag{3a}$$

Ferric/sulphide oxidation:

$$FeS_2 + 14\,Fe^{3+} + 8\,H_2O \rightarrow 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+ + \text{energy} \tag{3b}$$

The overall sulphide oxidation process can thus be presented as (Lottermoser, 2007):

$$4\,FeS_{2(s)} + 15\,O_2 + 14\,H_2O \rightarrow 4\,Fe(OH)_{3(s)} + 8\,H_2SO_4 + \text{energy} \tag{4}$$

The process leads to the generation of one mole of sulphuric acid for every mole of pyrite, with the acid in turn able to dissolve other minerals, salts and metals, as well as produce significant energy in the form of heat. The oxidation rate can be greatly enhanced by certain micro-organisms (biotic oxidation), although oxidation can still occur without microbial action (abiotic oxidation, with iron especially important). The primary aspects to note are the high amounts of water and oxygen required as well as the critical role of iron in generating acid. Although there can be numerous intermediate chemical steps and complex secondary minerals (e.g. sulphur) involved in sulphide geochemistry, the above equations are widely used to present the commonly observed outcomes, which are sulphuric acid, energy/heat and ferric hydroxides. The process can also be presented in the form of an ‘AMD engine’, shown in Figure 1, since the process can often be self reinforcing — explaining why AMD can last decades or longer.

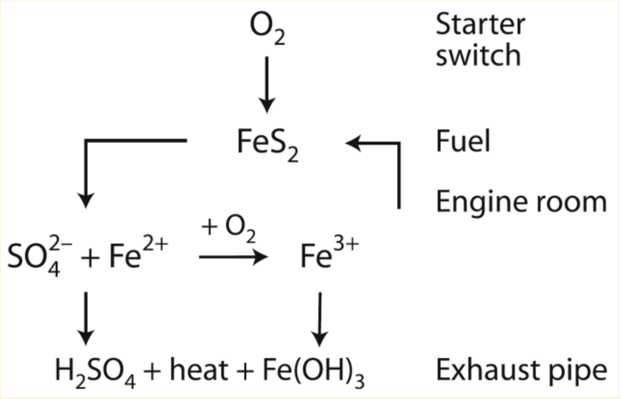

Figure 1 The self-sustaining, cyclic destruction of pyrite simplified as the AMD engine: oxidation of pyrite is initiated through oxygen (starter switch); pyrite, oxygen and iron (fuel) combust in the waste (engine room); and release Fe^{3+} hydroxides, sulphuric acid and heat into mine waters (exhaust pipe) (Lottermoser, 2007)

There are a variety of factors which affect the overall rate of sulphide oxidation:

- Particle size, porosity and surface area – in general, smaller particle sizes have a greater surface area, leading to higher reaction rates.
- Crystal and mineral structure – weaknesses in the structure of pyrite crystals/minerals can enhance access and thereby chemical attack.

- Trace element substitution – if a trace metal substitutes in the crystal/mineral structure, this can weaken the sulphide and make it more vulnerable to chemical reactions (e.g. arsenic in arsenopyrite).
- Other sulphides – if other sulphide minerals are in contact with the pyrite, this forms a galvanic cell, and the mineral with the highest electrode potential will be protected from oxidation (until exhaustion of the preferentially oxidised sulphide).
- Temperature – since the oxidation of pyrite is strongly exothermic (i.e. heat), this can help favour thermophillic bacteria, and the oxidation rate nearly doubles for every 10°C increase in temperate.
- Microbiological factors – a variety of micro-organisms, but especially acid- and heat-loving bacteria such as *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans* and *Thiobacillus thioparus*, can thrive and most significantly can enhance the conversion of iron and generation of acid (i.e. Equation (2)) up to several orders of magnitude.
- Oxygen concentrations – typically 21% in normal air, but has a low solubility in surface waters of 0–10 mg/L (depending on temperature and other factors). This leads to saturated sulphides being severely limited in their oxidation due to very low oxygen concentrations, while sulphides exposed to air undergoing considerably faster oxidation due to abundant oxygen.
- Carbon dioxide (CO_2) – CO_2 can be released from carbonate dissolution (e.g. calcite), providing a source of carbon for some anaerobic bacteria, which thereby enhances oxidation rates.
- Solution pH – the ferric (Fe^{3+}) iron concentration is very pH dependent. Above pH 3 Fe^{3+} will precipitate (Equation (3)) and be removed from further reactions, while below pH 3 Fe^{3+} is not removed from solution and reaction rates are considerably faster since the Fe^{3+} helps sulphide oxidation (see Figure (1)). Furthermore, some bacteria are pH-dependent, only thriving under highly acidic conditions and these in turn catalyse the oxidation step.
- Water – while some consider water crucial in oxidation, others argue its role is primarily as a reaction medium. In any case, cycles of wetting and drying are classic processes which can enhance oxidation, allowing oxidation products to be dissolved and removed, thereby exposing fresh pyrite.
- Fe^{2+}/Fe^{3+} solution ratio – depending on solution pH, Fe^{3+} may precipitate and limit oxidation rates, thereby making Equation (2) and the presence of oxygen as critical in facilitating the conversion of Fe^{2+} to Fe^{3+} – this makes the Fe^{2+}/Fe^{3+} ratio an important indicator of oxidation rates.

Once AMD has begun, the strongly acidic solutions (or leachate) can in turn dissolve salts, other minerals and heavy and trace metals present in the mine waste. It is common for AMD leachates to have low pH, high salinity and extremely high concentrations of trace and heavy metals often orders of magnitude above surface water and groundwater quality criteria (as well as drinking water). If this leachate enters the biosphere, it invariably presents extremely high risks of severe impacts, such as fish deaths, bioaccumulation and a variety of health and environmental impacts — just as Agricola described half a millennia ago.

A perhaps ironic curiosity of mining history is that the name-sake mines which began the British Rio Tinto company were in the Tinto region of southern Spain from the 1870s to the 1950s — a region renowned for metal mining from Roman times, especially lead and copper — yet the very name ‘Rio Tinto’ effectively means tainted river or red river in Spanish. This is, ironically, recognition of the ongoing impacts of AMD in the Tinto region for millennia. Despite the common belief that AMD is a relatively ‘recent’ problem in mining, it is indeed an ancient problem — the difference being the global scale, reach and a stronger environmental ethic in more recent decades.

The characteristics and nature of AMD problems at any mine site can vary considerably, though there are a number of common observations:

- Time lag (delay) – an initial lag period before AMD issues become noticeable is quite common, especially in arid zones, related to the time taken for pH to decline below 3 and oxidation accelerate.
- Longevity – once begun, AMD can continue to leach from mine wastes for decades or even up to millennia (as in the Tinto region of southern Spain). Some researchers have begun to argue the case for perpetual management of the potential long term impacts of AMD (e.g. Kempton et al., 2010).

- Heavy and trace metals – these are often site-specific and closely related to the ore being processed and associated mine wastes. For example, arsenic is commonly found in copper, nickel or gold ores, while selenium is common for coal, copper is widely present in AMD leachates, while other metals such as zinc, aluminium, lead or nickel are highly variable.

Another common scenario is near-neutral drainage, where there is significant oxidation occurring but the drainage passes through alkaline materials (e.g. dolomite) and this buffers the pH towards neutral. The leachate often contains high salinity but the dissolved metals will vary depending on their pH-redox controls. This is the reason why the most recent Australian guide (Taylor and Pape, 2007) uses the term ‘acid and metalliferous drainage’, since there are numerous cases whereby drainage is not strongly acidic but remains highly toxic to aquatic ecosystems. A compilation of examples of AMD leachates and Australian water quality criteria is shown in Table 1, demonstrating the toxic nature of AMD discharges.

Table 1 Examples of the chemistry of AMD leachates in Australia and Australian freshwater quality criteria (ANZECC and ARMCANZ, 2000)

	pH	**TDS**	**Al**	**Fe**	**SO_4**	**As**
Site	**-**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Mt Lyell	2.91–6.76	27–1,150	<0.01–19.5	0.04–20.6	1.1–6,434	<0.01–0.32
Mt Morgan	2.2–7.0	178–42,150	27–4,077	0.8–3,200	68–43,600	-
Rum Jungle (unrehabilitated)	-	-	-	-	160–471	-
Rum Jungle (after rehabilitation)	-	-	0.21–9	0.096–14	61–245	0.0006–0.041
ANZECC guidelines	-	-	0.027	ID	ID	0.001

Site (all µg/L)	**Co**	**Total Cu**	**Diss. Cu**	**Mn**	**Pb**	**Ni**	**Se**	**Zn**
Mt Lyell (unrehabilitated)	<10–2,100	0.5–37,500	0.25–35,000	0.05–40,000	<10–21,000	<10–1,130	<0.01–107	<10–5,030
Mt Morgan (unrehabilitated)	~1,800–5,800	400–340,000	-	1,200–389,000	-	~470–1,600	~3.3–14.8	1,000–180,000
Rum Jungle (unrehabilitated)	-	1,540–6,290	-	630–6,570	-	-	-	430–2,860
Rum Jungle (after rehabilitation)	53–480	140–1,100	20–390	260–2,000	2–880	53–430	-	49–670
ANZECC guidelines	ID	1	ID	1,200	1	8	5	2.4

Notes: ID – Insufficient Data (see ANZECC and ARMCANZ, 2000); ANZECC guideline values for freshwater ecosystems and 99% protection of biodiversity.

Sources: Mt Lyell – various sites, including river, waste rock and tailings delta samples (Davies et al., 1996; Taylor et al., 1996);
Mt Morgan – various sites, including downstream, open cut, waste rock and tailings seepage sites (Jones, 2001; Unger et al., 2003; Wels et al., 2009);
Rum Jungle – downstream water quality before and after rehabilitation (adapted from Kraatz, 1998; Pidsley, 2002; Mudd and Patterson, 2010).

Leachates derived from AMD can effectively occur wherever there is exposure of sulphidic minerals to oxygen and water, with the dominant sites including waste rock dumps, tailings, open pit walls or underground voids. It can be a trap to think that AMD is ‘natural’, but it must be remembered that the vast majority of sulphide minerals were not exposed prior to mining, and the nature of mining exposes the sulphides to both water and oxygen in the surface environment — it is therefore the act of mining sulphidic geology that effectively creates and exacerbates AMD problems. Typical AMD sources for a generic mine configuration are shown in Figure 2, with some surface water examples of AMD impacts are shown in Figure 3.

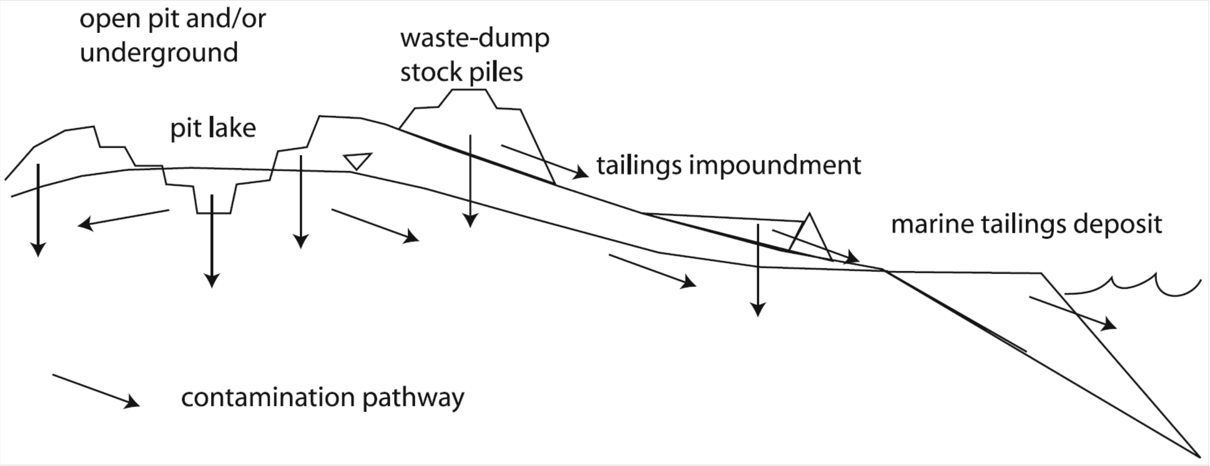

Figure 2 AMD sources for a typical mine configuration (Dold, 2008)

Figure 3 Examples of AMD impacts: top left – downstream of former Mt Oxide copper mine, Australia (~early 2009; source anonymous); top right – Mogpog River, downstream of failed tailings dam at former Marinduque Cu mine, Philippines (March 2004, photo Oxfam Australia); bottom left – downstream of Redbank copper mine, Australia (July 2009, photo Mineral Policy Institute); bottom right – AMD discharge (and dust in background) associated with former gold mining, West Rand, South Africa (October 2010, photo author)

3 Global mine waste generation

The global mining industry is vast, and covers the majority of the known elements (although many are only extracted in minor amounts). As discussed previously, the two principal types of mine waste are tailings and waste rock, with the amount of each generated dependent on global production and mine type. In general, underground mines generate more tailings than waste rock, while open cut can produce several tonnes of waste rock for every tonne of ore. A compilation of the major metals and minerals produced in 2009, the principal mining method, typical ore grades, waste rock-to-ore ratios and tailings and waste rock quantities is given in Table 2. Declining ore grades for select countries and metals are shown in Figures 4 and 5. Based on grades of remaining deposits and trends in exploration, the decline in ore grades is effectively terminal.

The estimates of mine waste in Table 2 are very approximate, but they do provide for a realistic sense of the true scale of mine wastes. Unfortunately, there is no data collected on the proportion of this waste which is sulphidic, the extent to which sulphidic wastes have been rehabilitated and how successful over time the rehabilitation is.

Table 2 Statistical compilation of global mining and mine waste for select commodities (2009 data)

	Iron Ore	Coal	Cu	Pb-Zn(-Ag)	Ni	Au	U
2009 production	1,588 Mt	5,842 Mt	15.8 Mt Cu	3.85 Mt Pb, 11.3 Mt Zn	1.35 Mt Ni	2,572 t	51.0 kt U
Typical grades	50%	-	0.7% Cu	2% Pb, 5% Zn	1.3% Ni	2.5 g/t	0.1% U
Ore proc. (Mt)	1,650	7,300	2,800	260	140	1,200	60
Mill recovery	98%	80%	80%	~82.5% Pb+Zn	75%	90%	90%
% Open cut	98%	70%	70%	50%	50%	75%	30%
Waste:ore (underground)	0.2	0.2	0.1	0.2	0.2	0.25	0.5
Waste:ore (OC)	2	5	5	7.5	2	5	5
Tailings (Mt)	175	1,500	2,750	220	130	1,200	60
Waste rock (Mt)	3,240	26,000	10,000	1,000	150	4,400	105
Sulphidic waste?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E.g. references	[1]	[2]	[3]	[4]	[5]	[6]	[7]

Sources: All data is approximate only, and adapted from ABARE (2010), Mudd (2009a, 2009b, 2010a, 2010b, and unpublished data). OC – open cut. [1] Porterfield et al. (2003), Hughes et al. (2009); [2] Bucknam et al. (2009); [3] Davies et al. (1996); [4] Gao and Bradshaw (1995); [5] Blowes et al., (2003); [6] Winde and van der Walt (2004); [7] Merkel and Hasche-Berger (2005).

In considering the sheer mass of mine waste produced annually — at least 50 billion tonnes per year and growing exponentially (with this figure not including bauxite-alumina, aggregates and other commodities) — even if only a minority was sulphidic, this represents at least several billion tonnes requiring pro-active environmental assessment, monitoring and rehabilitation. The waste is cumulative also — that is, it is the sum total of all historic and new mine waste which requires ongoing monitoring and maintenance, until such time as long-term stability and isolation has been confidently proven.

It is critical to note that some polluting AMD sites, like Rum Jungle, have been rehabilitated but this work was failing less than a decade later (see Mudd and Patterson, 2010), meaning we need to be very cautious rather than simply optimistic in projecting future behaviour of AMD wastes and their rehabilitation and environmental impacts.

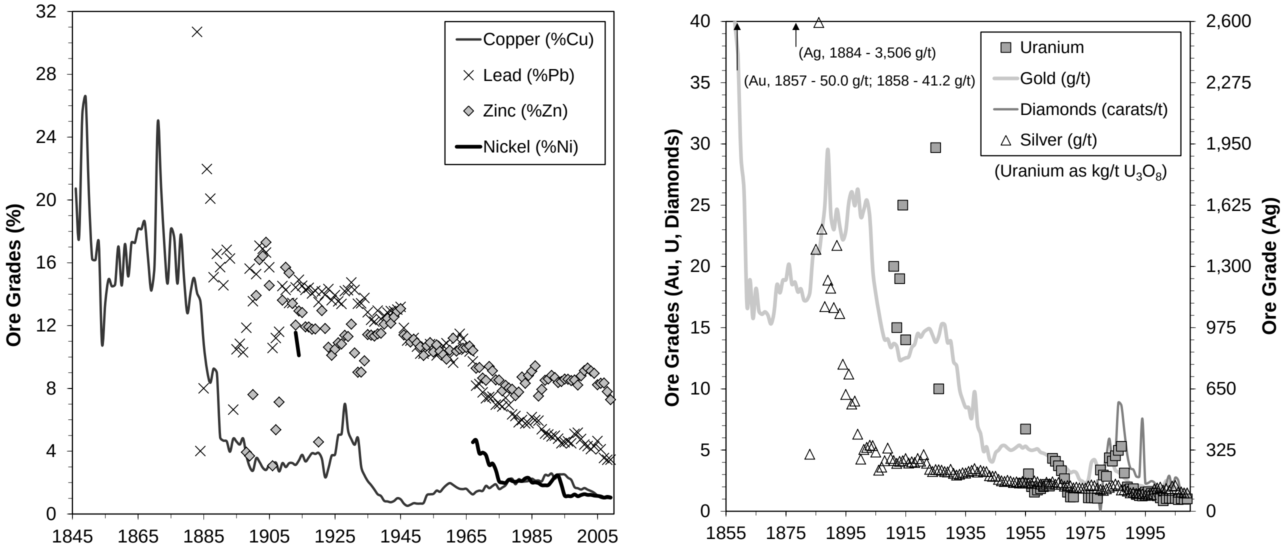

Figure 4 Declining Australian average ore grades over time (data updated from Mudd, 2009a)

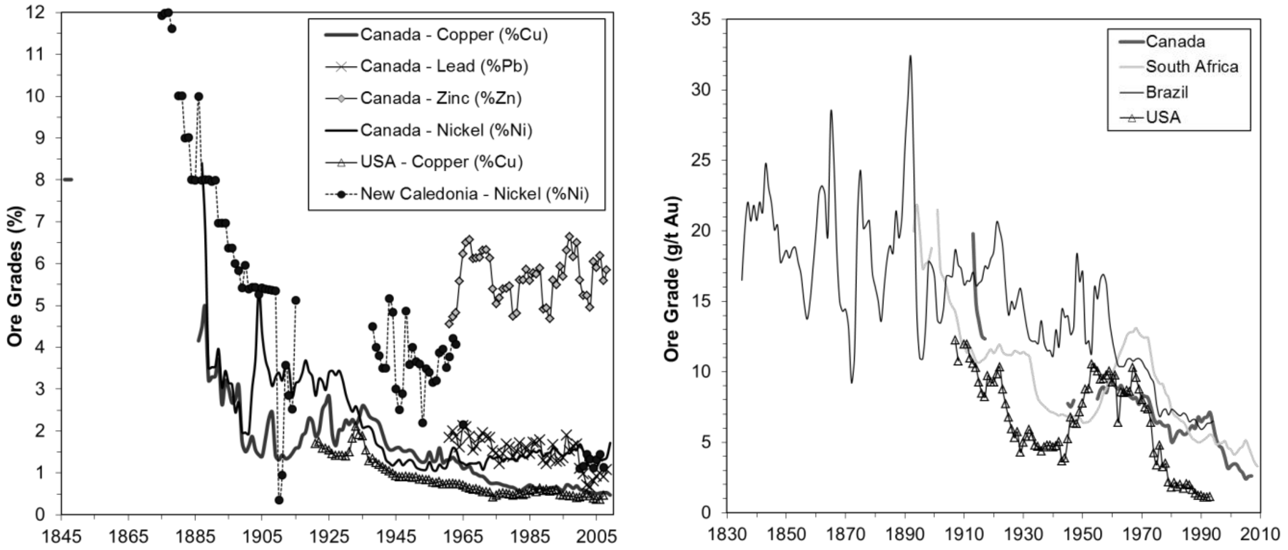

Figure 5 Declining ore grades: left – select country base metal ore grades (Mudd, 2009b); right – gold ore grades (data updated from Mudd, 2007)

4 Common approaches to assessing and managing AMD risks

There are a growing number of approaches to the identification and management of AMD risks associated with mine waste, and these will only be briefly reviewed here. For more extensive detail, see Parker and Robertson (1999), Taylor and Pape (2007) or Spitz and Trudinger (2008), as well as national research programs and international collaborations such as:

- MEND, Canada – Mine Environment Neutral Drainage program (1989–2009, and extensions; see www.nrcan-rncan.gc.ca./mms-smm/tect-tech/sat-set/med-ndd-eng.htm).
- ACMER – Australian Centre for Minerals Extension and Research leads a national research effort on AMD issues (recently changed name to SMI Knowledge Transfer) (www.acmer.uq.edu.au).
- ADTI, USA – Acid Drainage Technology Initiative (www.aciddrainage.com).

- PADRE – Partnership for Acid Mine Drainage in Europe (www.padre.imwa.info).
- SAWRC – South African Water Resource Commission (www.wrc.org.za).
- GARD – Guide to Acid Rock Drainage produced as an online resource by the International Network for Acid Prevention (INAP) (see www.gardguide.com).

The main stages of AMD risk management for new mines are assessment and testing, design and implementation, and monitoring. At legacy or abandoned sites, the issue of cheap perpetual treatment versus expensive rehabilitation also has to be considered. This section will review AMD assessment, design approaches, treatment and long-term monitoring, although the distinction can sometimes be minor.

4.1 AMD assessment

A wide variety of laboratory and field tests have been developed and standardised over recent years to allow the thorough characterisation and assessment of AMD risks from mine wastes — beginning with the exploration stage right through to mine closure and rehabilitation. In addition, various theoretical methods have been developed to help guide the longer-term assessment process.

The most common theoretical accounting method is the acid-base account (ABA), which represents the ability of a material to produce and/or consume acid, and is also known as the net acid producing potential (NAPP) test (in units of kg H_2SO_4/t). The NAPP can be broken down into the maximum potential acidity (MPA) and the acid neutralising capacity (ANC), whereby NAPP = MPA – ANC. The MPA/ANC ratio can also be used to assess the factor of safety. The concentration of sulphur can be used as a measure of potential sulphide content, but not all sulphur will be present as pyritic sulphide, nor will all sulphides readily oxidise and generate acid. Given the variety of complex factors which control AMD, a rapid laboratory oxidation test called the net acid generation (NAG) test can be performed. Both NAPP and NAG tests are classed as 'static' tests, since they are effectively instant tests and not done over time. When combined with careful sampling, NAPP and NAG testing can help provide a valuable, initial assessment of AMD risks and reduce uncertainty in any projections. A geochemical classification scheme, based on NAPP-NAG tests, can be applied to a material as potentially acid forming (PAF), potentially acid forming-low capacity (PAF-LC), non-acid forming (NAF), acid consuming (ACM) or lastly uncertain, as shown in Table 3.

Table 3 Goechemical classification of AMD potential for sulphidic wastes (Taylor and Pape, 2007)

Primary Geochemical Material Type	NAPP (kg H_2SO_4/t)	NAG pH
Potentially acid forming (PAF)	>10*	<4.5
Potentially acid forming-low capacity (PAF-LC)	0 to 10*	<4.5
Non acid forming (NAF)	Negative	≥4.5
Acid consuming (ACM)	Less than -100	≥4.5
Uncertain#	Positive	≥4.5
	Negative	<4.5
	Positive	<4.5

Notes: *Site-specific but typically in the range 5–20 kg H_2SO_4/t; #Further testing required to confirm material classification. Any local guidelines and statutory requirements should also be checked.

Further laboratory testing should include mineralogical and elemental composition, as these give important insights into the potential acid-base behaviour as well as potential elements which might have environmental significance.

The next major group of AMD testing are kinetic tests, generally designed to determine sulphide oxidation rates, chemical kinetics, lag times, test larger samples (or mixes), leachate chemistry, or to assist in scale-up predictions. Kinetic tests involve leaching over time, and can be conducted on a bench-top scale in the laboratory or involve large heaps or special columns in the field. Given the direct measurements obtained from kinetic tests, the data obtained is often used for modelling purposes.

All assessment and characterisation work should be designed to inform a more comprehensive environmental impact and risk assessment and environmental management system (e.g. using the ISO 14000 series), as well as meeting any local statutory requirements.

4.2 Design approaches

The primary driver of AMD is the exposure of sulphidic wastes to water and oxygen – leading to the need to isolate the sulphidic material from water, oxygen or both. There are essentially two design approaches to achieve this – treatment or isolation, with the choice largely dependent on whether the site is an abandoned or legacy site, or operating or proposed mine, and various site-specific factors (especially climate and environmental sensitivity). Isolation can be incorporated into mine designs and planning, and treatment is reviewed in the next section.

The most common way to isolate AMD wastes is through careful mine planning, segregation and selective placement of PAF materials and encapsulation by benign wastes (e.g. limestone). Factors which require careful consideration include topography, climate and surface water and groundwater aspects. A simple example of encapsulation is shown in Figure 6, with analogous concepts able to be applied for tailings dams. A similar variation on this approach is co-mixing, often considered for tailings placement in waste rock dumps (Wilson et al., 2003a).

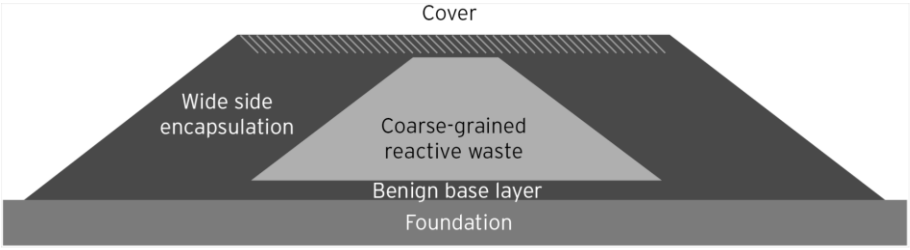

Figure 6 Encapsulation of reactive sulphidic waste inside benign mine (Taylor and Pape, 2007)

Another common isolation design approach is the use of water covers, since this will reduce the oxygen availability considerably. Water covers, most commonly used for tailings storages, will only work well if they can maintain a minimum water depth, and thus are principally used in wet environments.

4.3 Treatment

There are a variety of treatment approaches which can be used to address AMD problems, primarily dependent on local environmental conditions, extent and nature of mine wastes. Some of the most common approaches includes limestone drains (which are very cheap but rarely effective in the long run, since ferrihydrite coats the surface and limits contact of AMD leachate with the calcite), engineered wetlands to treat acidity and precipitate metals, or in some cases full water treatment plants. The various programs noted earlier have extensive papers on such treatment options.

One of the most popular long term treatment methods (though it could also be argued to be an isolation approach) is the design and construction of multi-layered engineered soil covers over AMD wastes (tailings or waste rock). Depending on climatic conditions, such as arid, temperate or tropical, a soil cover can be engineered to ensure that a particular layer stays effectively saturated to minimise oxygen ingress, or the cover can be designed to limit both infiltration and oxygen. Based on the different hydraulic and moisture storage characteristics of various soils, it is possible to design a multi-layered cover system which can achieve the aim of minimising oxygen, infiltration or both. The calculations to size each layer are based on unsaturated flow mechanics coupled with algorithms to accurately account for soil moisture-vegetation-climate interactions (e.g. Vadose/W or SVFlux). The principal approach is to choose soil types to perform a given function, such as a moisture storage layer, a capillary break or clay barrier, with the design intended to make sure the clay layer stays saturated and thereby minimises oxygen ingress.

The capillary break layer is particularly important, as it takes advantage of the soil moisture characteristics of differing soil types such as clays, silts or sands. As shown in Figure 7, the progression from gravels to sands, silts and clays gradually increases the moisture retention capacity of each soil type, respectively, but under unsaturated flow conditions, silts and clays can retain moisture up to much higher negative pore pressures (suction) than coarser soils. At a given suction, a gravel or sand will desaturate while a silt or clay will retain moisture — if the silt is above a sand, the sand acts as a capillary break or discontinuity in soil moisture. The basic cover concepts and designs are shown in Figure 8.

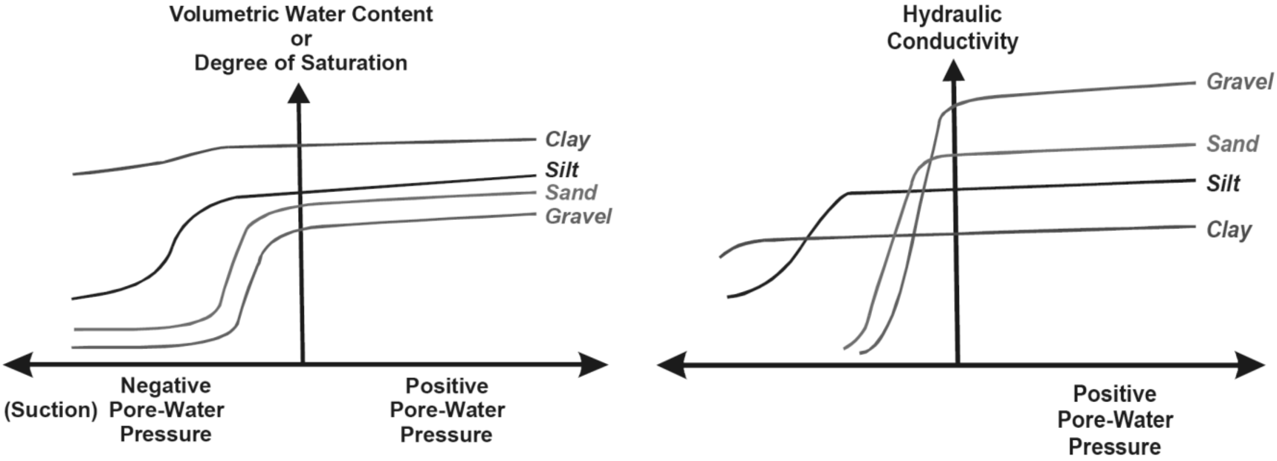

Figure 7 Standard curves for soil moisture versus pore pressure (left) and soil moisture versus hydraulic conductivity (right) (O'Kane et al., 2002)

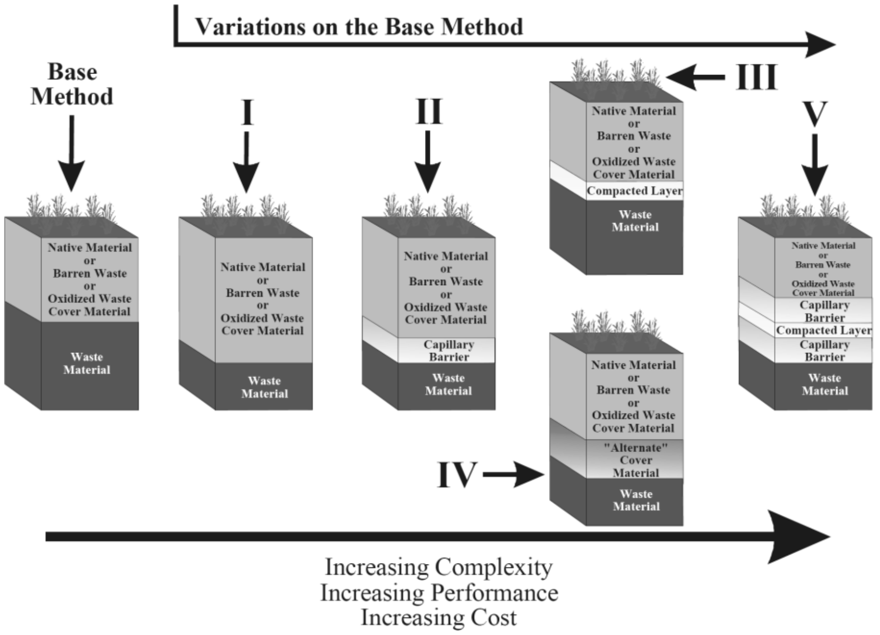

Figure 8 Principal concepts for engineered soil covers (O'Kane et al., 2002)

Covers are now widely used in remediating AMD wastes, but there are very few sites which are older than a decade or two. Rehabilitated mine sites in Australia with covers a decade old or more include Rum Jungle, Mary Kathleen, Captain's Flat, Kidston and Brukunga, or Equity Silver in Canada (amongst others). It seems common that monitoring rarely lasts beyond a few years after cover installation, despite the long-term nature of AMD risks. There appears to be no comprehensive assessment of cover performance at all rehabilitated sites to date, though at the rare sites which are well documented there are clear signs of cover failure leading to increased AMD generation and impacts (e.g. Rum Jungle; see Mudd and Patterson, 2010). Ongoing assessment of most of these older sites has shown that the most critical issues are careful cover design, methodical cover construction, ensuring soil types used do meet the design criteria – especially specific clay types (i.e. avoid cracking clays), allowance to cope with extreme events (e.g. high rainfall or long drought) and management of vegetation (see Wilson et al., 2003b; Mudd and Patterson, 2010). Over time, as experience has grown with different cover designs in varying climates, regulatory requirements are moving to the more complex, expensive covers (or to the right in Figure 8).

4.4 Long term monitoring

Successful management of AMD risks requires both short and long-term monitoring. Given the time lag and longevity of AMD issues, and remembering that some are arguing for monitoring and management in perpetuity, it is critical that monitoring is ongoing, usable, and well documented, analysed and communicated. For example, if monitoring begins to show signs of AMD breakthrough, it is invariably cheaper and easier to intervene urgently rather than wait until the AMD has accelerated and become considerably more difficult and expensive to address.

5 P&TT and AMD risks

P&TT can be considered as a continuum from a low slurry density, where the slurry effectively behaves as a fluid, to a high density 'paste' where the fluid exhibits non-Newtonian behaviour (Boger, 2009). The solids concentration can vary from 20% to >75%, with the rheological behaviour related to aspects such as clays, solution chemistry and other factors. The original incentive for developing P&TT technology was the desire to develop stable tailings storage facilities for the Kidd Creek poly-metallic mine in Canada in the 1970s, followed a decade later by the need to remove water from tailings disposal at alumina refineries, thereby improving process efficiency and significantly reducing the environmental footprint and associated impacts. It is now well recognised that, over the long-term, P&TT leads to lower administration, construction and rehabilitation costs for tailings and substantially lower water use and environmental impacts (e.g. wildlife deaths, more stable tailings facilities) (Dow and Minns, 2004; Jewell and Fourie, 2006; Franks et al., 2011).

The major issue which appears to be missing from P&TT literature, however, is AMD risks. Based on the previous Paste conferences from 2005–2010, only one paper appears to address the interaction of P&TT with AMD issues (Wilson et al., 2006 — which examines the use of 'paste rock' as a cover material), while another paper examines evaporation rates, unsaturated flow and oxidation of gold paste tailings (Fisseha et al., 2009). Fall et al. (2009) investigated bentonite paste tailings mixtures for barriers (covers or liners) in AMD mitigation, demonstrating significant cost savings compared to conventional designs. An important study by Bryan et al. (2010) reviewed the drying of thickened tailings and subsequent oxidation behaviour of the sulphidic wastes — showing that oxidation does occur in surface layers as tailings dry and allow oxygen ingress (e.g. Bulyanhulu gold mine, Tanzania; Kidd Creek base metals mine, Canada), although this could be actively managed through drying time and stacking management. A detailed study of oxidation rates of surface deposited paste tailings at the La Ronde Cu-Zn-Au-Ag mine in Canada showed that sulphide oxidation can readily proceed, although the careful addition of a binder such as Portland cement can significantly reduce oxidation (Deschamps et al., 2008). Thus there appear to be few studies and research addressing this area, though work is increasing rapidly and could be a new positive basis for P&TT.

The soil moisture retention curves for typical soils were shown in Figure 7, and although such curves are not widely known for P&TT (one test is given in Fisseha et al., 2010), it can reasonably be expected that they would be similar to silts or clays. As such, it would appear that the following aspects are critical in mitigating AMD generation from the tailings directly:

- Water and degree of saturation – if the P&TT are permanently saturated (i.e. no air in voids or pore space), this will help to significantly reduce the potential for oxidation (similar to a compacted layer in cover designs) – underground P&TT storage should therefore help to ensure high degrees of saturation due to non-existent evaporation rates and rebounding groundwater levels.
- Binder – if a cement binder is used, this can help in reducing oxidation rates, but it requires careful management to ensure minimal sulphide oxidation occurs (or in worst case scenarios actually enhances oxidation behaviour).
- Residence time – ensuring that each layer of P&TT is optimised for deposition versus oxidation.

Overall, there appears to be some highly encouraging research and sound technical reasons to argue that paste and thickened tailings could indeed be used in the mitigation and management of AMD risks from large volume mine wastes. Although most research at present is focused on tailings directly, there is good reason to expect that P&TT could help in waste rock AMD issues also (i.e. through co-disposal or possibly through 'paste rock'), especially given the sheer scale of waste rock produced across the global mining industry. However, there is also evidence that P&TT does not simply eliminate AMD risks, and it requires careful and pro-active monitoring and management.

6 Conclusion

The potential scale of acid and metalliferous drainage risks from tailings and waste rock across the global mining industry is enormous, and growing exponentially as well as being cumulative in environmental terms. Due to declining ore grades and the increased use of open cut mining, combined with continually growing minerals demand, the problems of mine waste will only escalate. Although AMD risks from mine wastes can be quite complex, since many factors vary from site to site, the basic process of sulphide oxidation leads to mammoth environmental risks — such as polluted surface waters, groundwater and significantly reduced biodiversity. Once the process has begun, it can take years to develop but last decades or centuries. There has been significant growth in paste and thickened tailings technology and use over the past decade, and it certainly appears that there are indeed good technical reasons to argue that P&TT can help in addressing AMD risks from tailings and/or waste rock. Given the scale of legacy and polluting mine sites, which were much smaller than present mines but where AMD is invariably the cause of the pollution, it is clear that prevention is not only better than cure but considerably cheaper. There is a clear need for more research, and especially longer term site studies, but paste and thickened tailings can indeed act as a friend against acid and metalliferous drainage, helping to make the industry more sustainable in its management of mine waste.

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References

ABARE (2010) Australian Commodity Statistics 2010, Australian Bureau of Agricultural and Resource Economics (ABARE), Canberra, ACT, 376 p.

Agricola, G. (1556) De Re Metallica, Translated by H.C. Hoover and L.H. Hoover (1912), Dover Publications, 1950 Edition, New York, USA.

ANZECC and ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality, National Water Quality Management Strategy, Australian & New Zealand Environment & Conservation Council (ANZECC) and Agricultural & Resource Management Council of Australia & New Zealand (ARMCANZ), Canberra, ACT, October 2000.

Blowes, D.W., Ptacek, C.J., Jambor, J.L. and Weisener, C.G. (2003) The Geochemistry of Acid Mine Drainage, in Treatise on Geochemistry, H.D. Holland and K.K. Turekian (eds), Vol. 9, Chap. 9.05, pp. 149–204.

Boger, D.V. (2009) Rheology and the Resource Industries, Chemical Engineering Science, Vol. 64, No. 22, pp. 4525–4536.

Bryan, R., Simms, P. and Verburg, R. (2010) Coupling Oxidation to Transient Drying During Multilayer Deposition of Thickened Gold Tailings, Minerals Engineering, Vol. 23, No. 14, pp. 1101–1112.

Bucknam, C.H., Perry, E., Turner, D., Figueroa, L.D., Castendyk, D., Eary, L.E. and Gusek, J.J. (2009) Update on the Acid Drainage Technology Initiative (ADTI), the INAP Global Alliance Member Representing the United States, in Proceedings Eighth International Conference on Acid Rock Drainage (8th ICARD), Skelleftea, Sweden, June, 11 p.

Davies, P., Mitchell, N. and Barmuta, L. (1996) The Impact of Historical Mining Operations at Mount Lyell on the Water Quality and Biological Health of the King and Queen River Catchments, Western Tasmania, Office of the Supervising Scientist (OSS), Canberra, ACT, Supervising Scientist Report 118, 149 p.

Deschamps, T., Benzaazoua, M., Bussière, B., Aubertin, M. and Belem, T. (2008) Microstructural and Geochemical Evolution of Paste Tailings in Surface Disposal Conditions, Minerals Engineering, Vol. 21, No. 4, pp. 341–355.

Dold, B. (2008) Sustainability in Metal Mining: From Exploration, Over Processing to Mine Waste Management, ReViews in Environmental Science and Biotechnology, Vol. 7, No. 4, pp. 275–285.

Dow, J.A.S. and Minns, A.J. (2004) Translating the Challenges of Sustainability and Eco-Efficiency Into Improved Business Performance at Newmont Operations, in Proceedings Green Processing 2004: 2nd International Conference on the Sustainable Processing of Minerals, AusIMM, Fremantle, WA, May 2004, pp. 21–26.

European Environment Bureau (EEB) (2000) The Environmental Performance of the Mining Industry and the Action Necessary to Strengthen European Legislation in the Wake of the Tisza-Danube Pollution, EEB, Brussels, Belgium, EEB Document 2000/016, October 2000, 32 p.

Fall, M., Celestin, J.C. and Han, F.S. (2009) Suitability of Bentonite-Paste Tailings Mixtures as Engineering Barrier Material for Mine Waste Containment Facilities, Minerals Engineering, Vol. 22, No. 9–10, pp. 840–848.

Fisseha, B., Bryan, R. and Simms, P. (2009) Evaporation, Unsaturated Flow and Oxidation in Multilayer Deposits of Gold Paste Tailings, in Proceedings 12th International Seminar on Paste and Thickened Tailings (Paste09), R.J. Jewell, A.B. Fourie, S. Barrera, J. Wiertz (eds), 21–24 April 2009, Viña Del Mar, Chile, Gecamin Limited, Santiago, Australian Centre for Geomechanics, Perth, pp. 251–260.

Fisseha, B., Bryan, R. and Simms, P. (2010) Evaporation, Unsaturated Flow, and Salt Accumulation in Multilayer Deposits of “Paste” Gold Tailings, ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 136, No. 12, pp. 1703–1712.

Franks, D.M., Boger, D.V., Côte, C.M. and Mulligan, D.R. (2011) Sustainable Development Principles for the Disposal of Mining and Mineral Processing Wastes, Resources Policy, Online First, doi:10.1016/j.resourpol.2010.12.001.

Gao, Y. and Bradshaw, A.D. (1995) The Containment of Toxic Wastes: II, Metal Movement in Leachate and Drainage at Parc Lead-Zinc Mine, North Wales, Environmental Pollution, Vol. 90, No. 3, pp. 379–382.

Hughes, A., Dineen, R. and Kent, S. (2009) Environmental Performance of the Savage River Rehabilitation Project, in Proceedings Eighth International Conference on Acid Rock Drainage (8th ICARD), Skelleftea, Sweden, June, 10 p.

Jewell, R.J. and Fourie, A.B. (eds) (2006) Paste and Thickened Tailings – A Guide, 2nd edition, Australian Centre for Geomechanics, Perth, 242 p.

Jones, D. (2001) Contaminant Source Study, Mt Morgan Mine, Prepared by EWL Sciences for Queensland Department of Natural Resources and Mines (QNRM), Report QME 255, Darwin, NT, May 2001, 64 p.

Kempton, H., Bloomfield, T.A., Hanson, J.L. and Limerick, P. (2010) Policy Guidance for Identifying and Effectively Managing Perpetual Environmental Impacts From New Hard Rock Mines, Environmental Science and Policy, Vol. 13, No. 6, pp. 558–566.

Kraatz, M. (ed) (1998) Rum Jungle Rehabilitation Project Monitoring Report 1988–93, Land Resources Division, NT Deptartment of Lands, Planning & Environment (NTDLPE), March, Palmerston, 180 p.

Langmuir, D. (1997) Aqueous Environmental Geochemistry, Prentice Hall, Upper Saddle River, New Jersey, 600 p.

Lottermoser, B. (2007) Mine Wastes – Characterisation, Treatment, Environmental Impacts, 2nd Edition, Springer-Verlag, Berlin, Germany, 291 p.

Merkel, B.J. and Hasche-Berger, A. (eds) (2005), Uranium in the Aquatic Environment, Fourth International Conference Uranium Mining and Hydrogeology IV (UMH-4), Springer, September, Freiberg, Germany, 976 p.

Mudd, G.M. (2007) Global Trends in Gold Mining: Towards Quantifying Environmental and Resource Sustainability? Resources Policy, Vol. 32, No. 1–2, pp. 42–56.

Mudd, G.M. (2009a) The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future, Research Report No RR5, Department of Civil Engineering, Monash University and Mineral Policy Institute, Revised – April 2009, 277 p.

Mudd, G.M. (2009b) Historical Trends in Base Metal Mining: Backcasting to Understand the Sustainability of Mining, in Proceedings 48th Annual Conference of Metallurgists – Green Technologies for Mining and Metallurgical Industries, Canadian Metallurgical Society, Sudbury, Ontario, Canada, August, pp. 273–284.

Mudd, G.M. (2010a) Global Trends and Environmental Issues in Nickel Mining: Sulphides versus Laterites, Ore Geology Reviews, Vol. 38, No. 1–2, pp. 9–26.

Mudd, G.M. (2010b) The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints, Resources Policy, Vol. 35, No. 2, pp. 98–115.

Mudd, G.M. and Patterson, J. (2010) Continuing Pollution from the Rum Jungle U-Cu Project: A Critical Evaluation of Environmental Monitoring and Rehabilitation, Environmental Pollution, Vol. 158, No. 5, pp. 1252–1260.

O’Kane, M., Ayres, B., Christensen, D. and Meiers, G. (2002) CANMET – CETEM Manual on Cover System Design for Reactive Mine Waste, Saskatoon, Canada, O’Kane Consultants Inc, 160 p.

Parker, G. and Robertson, A. (1999) Acid Drainage, Australian Minerals & Energy Environment Foundation, Occasional Paper No. 11, Melbourne, 239 p.

Pidsley, S.M. (ed) (2002) Rum Jungle Rehabilitation Project Monitoring Report 1993–1998, NT Deptartment of Infrastructure, Planning & Environment (NTDIPE), July, Palmerston, NT, 247 p.

Porterfield, D.C., Miller, S. and Waters, P. (2003) A Strategy for Managing Acid Rock Drainage in Arid Climates – The Mt Whaleback Story, in Proceedings Sixth International Conference on Acid Rock Drainage (6th ICARD), T. Farrell and G. Taylor (eds), Australasian Institute of Mining & Metallurgy, Cairns, Australia, July, pp. 143–146.

Spitz, K. and Trudinger, J. (2008) Mining and the Environment – From Ore to Metal, CRC Press, Taylor & Francis Group, 891 p.

Taylor, J. and Pape, S. (eds) (2007) Managing Acid and Metalliferous Drainage, Leading Practice Sustainable Development Program for the Mining Industry, Commonwealth Department of Industry, Tourism and Resources, Canberra, ACT.

Taylor, J.R., Weaver, T.R., McPhail, D.C. and Murphy, N.C. (1996) Characterisation and Impact Assessment of Mine Tailings in the King River System and Delta, Western Tasmania, Office of the Supervising Scientist (OSS), Canberra, ACT, Supervising Scientist Report 105, 135 p.

Unger, C., Laurencont, T., Keliher, L., McCombe, C. and Bartley, G. (2003) Rehabilitation Plan for the Mount Morgan Minesite, Central Queensland, Queensland Department of Natural Resources & Mines (QNRM), Brisbane, November, 325 p.

Wels, C., Findlater, L. and McCombe, C. (2009) Contaminant Load Balance for Mount Morgan Mine, Qld, Australia, in Proceedings Eighth International Conference on Acid Rock Drainage (8th ICARD), Skelleftea, Sweden, June, 10 p.

Wilson, G.W., Plewes, H.D., Williams, D.J. and Robertson, J. (2003a) Concepts for Co-Mixing of Tailings and Waste Rock, in Proceedings Sixth International Conference on Acid Rock Drainage (6th ICARD), T. Farrell and G. Taylor (eds), Australasian Institute of Mining & Metallurgy, Cairns, Australia, July, pp. 437–443.

Wilson, G.W., Williams, D.J. and Rykaart, E.M. (2003b) The Integrity of Cover Systems – An Update, in Proceedings Sixth International Conference on Acid Rock Drainage (6th ICARD), T. Farrell and G. Taylor (eds), Australasian Institute of Mining & Metallurgy, Cairns, Australia, July, pp. 445–451.

Wilson, G.W., Miskolczi, J., Dagenais, A.M., Smith, Q., Lanteigne, L., Hulett, L. and Landriault, D. (2006) The Application of 'Paste Rock' for Cover Systems in Mine Waste Management, in Proceedings Ninth International Seminar on Paste and Thickened Tailings (Paste06), R.J. Jewell, S. Lawson and P. Newman (eds), 3–7 April 2006, Limerick, Ireland, Australian Centre for Geomechanics, Perth, pp. 209–220.

Winde, F. and van der Walt, I.J. (2004) The Significance of Groundwater-Stream Interactions and Fluctuating Stream Chemistry on Waterborne Uranium Contamination of Streams – A Case Study From a Gold Mining Site in South Africa, Journal of Hydrology, Vol. 287, No. 1–4, pp. 178–196.