THE MCARTHUR RIVER PROJECT:

THE ENVIRONMENTAL CASE FOR COMPLETE PIT BACKFILL

Dr Gavin M. Mudd

mineral policy institute

This report is dedicated to the Gurdanji, Mara, Garawa and Yanyuwa Peoples and their continuing struggle to protect country from invasive mining.

ACKNOWLEDGEMENTS

Research: Gavin Mudd, Charles Roche and Lauren Mellor

We recognise and pay tribute to the communities, researchers and mining professionals who have long understood the need for mining legacies reform in Australia.

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ABOUT THE MINERAL POLICY INSTITUTE

The Mineral Policy Institute [MPI] is an international civil society organisation with a volunteer board representing members from across the world. Operating from Australia we focus on assisting communities affected by specific mining projects and on achieving industry reform through improvements to policy, law and practice.

With a strong emphasis on free prior and informed consent, MPI undertakes a supportive and background role to assist mining affected communities. Our aim, and our role is to support communities to more effectively protect their rights and respond to mining issues that impact on them.

While mining disproportionately impacts the developing world, however, the decisions that govern these projects are made and need to be influenced in the developed world. MPI has the expertise, the experience and the networks to assist communities and to access the many mining companies based in Australia [also US, UK, South Africa and Canada] and their investors from around world.

We are guided by a vision of a just and sustainable mineral cycle where human rights are protected, impacts dramatically reduced and mineral/fuel efficiency and reuse is paramount. While we believe that minerals/fuel are central to the quality of human life today, the benefits of the current minerals systems are greatly skewed to a relatively small global elite. MPI plays a key role in addressing this paradox… to increase the equitable distribution of the benefits while decreasing the social injustices and environmental impacts of the mineral/fuel system.

As an industry watchdog, we rely on community funding to ensure our independence from industry. Seeking to improve and influence an industry that plans in decades, we require funding to progress and achieve long-term strategic goals and to assist communities who are impacted by mining today, tomorrow and in the future.

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INTRODUCTION AND BACKGROUND

The McArthur River lead–zinc–silver (Pb–Zn–Ag) mining project is located in the central eastern region of the Northern Territory (NT) of Australia, home to the Gurdanji, Mara, Garawa and Yanyuwa Peoples. Discovered in the late 1950's and mined since the mid-1990's the deposit remains one of the world's largest mineral resources of Pb–Zn–Ag (Mudd *et al*, 2016). The McArthur River, from which the mine takes its name, is seasonal, changing from a chain of ponds in the dry to a tropical torrent in the wet season on its 300km journey to the Gulf of Carpentaria.

In terms of Australian and world Pb–Zn mining, the project is technically difficult and has had a challenging history—on many fronts. The initial challenges faced by McArthur River were predominantly technical in nature with the very fine-grained ore being difficult to treat with the standard ore processing (or milling) technology of the time, resulting in the project laying dormant until the early 1990's when improvements in technology finally allowed development (see Mudd, 2007; Mudd *et al*, 2016). The deposit lies mostly under the McArthur River itself, which forced the use of underground mining initially until the technical challenges and poor economics of this approach necessitated the switch to larger scale open cut mining and diversion of the project's namesake river in the mid-2000's—but with considerable controversy and protracted litigation by the indigenous community (e.g Howey, 2010; Young, 2015). In recent years, major concerns have been raised over acid mine drainage, waste rock, tailings and water management—especially plumes of smoke originating from the waste rock—and the implications for the longer term future of the project area.

The mines controversial history cannot be read in isolation; rather it is represents a continuation of a history of neglect and suppression of the Aboriginal people from Borroloola, which is only exceeded by the trauma of the many massacres by settlers and government agents (Roberts, 2005). The early years of exploration, the impact of the first mining proposal and the response from local communities to mining was well captured by the film 'Two Laws'[1]. In it we hear not just of the clash of laws, but a clash of value systems, with the traditional owners fighting to control their own land and future. During the late 1970's to early 1990's, this struggle for indigenous land rights was opposed by the joint efforts of the NT Government and MIM, who were later supported by a Federal Government in the 1990's keen to fast track the mine to mollify the mining industry and international investors after the Mabo decision and the establishment of native title (Young, 2015).

Long before the community resorted to legal challenges (discussed later) to the mine, they had been raising strong objections to it, particularly in relation to the protection of sacred sites and potential environmental impacts, especially to the McArthur River. Young writes of the ***"…aboriginal traditional owners being subject to governmental pressure, obstruction and chicanery at almost every turn"*** (2015 p.15). This is not to say that opposition to the mine was universal, far from it, but concern over the environment was strong and at the heart of all concerned, whether in favour of the mine proceeding or not. Concern about and opposition to the mine has continued, with spikes of resistance occurring in relation to the river diversion, the 'burning waste dump', potential contamination of the river, fish and grazing cows, pollution issues at the Bing Bong Port and the inaccessibility of cultural sites on the mining lease.

While not the focus of this report, the cultural, social and environmental history of the region and the actual and potential impacts from McArthur River mine is a dominant factor in the region. Denied of control, the local communities continue to bare the brunt of the negative impacts, while government and industry collude to deny and downplay impacts.

This report is a review of the current state of technical issues at the McArthur River project, including the site history, environmental impact assessment (EIA) history, waste rock, tailings and water management and associated acid mine drainage issues. It examines the technical arguments for and against complete backfill of waste and tailings into the eventual final void, thereby achieving environmental outcomes that are aligned with community expectations for mine site closure and rehabilitation. It is unfortunate that so much of the information about the McArthur River project remains uncertain or unpublished, limiting transparency and independent analysis—especially since elsewhere the Australian mining industry is adopting greater openness in reporting and access to data (e.g. Newcrest Mining and Cadia).

The report provides a unique and independent assessment of the issues and risks which need to be considered in detail and possible future outcomes for the McArthur River project, especially long-term environmental outcomes relating to mine wastes.

1 A 1981 documentary by the Borroloola Aboriginal Community with Carolyn Strachan & Alessandro Cavadini.

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BRIEF HISTORY AND STATISTICS OF THE MCARTHUR RIVER PROJECT

The occurrence of Pb–Zn mineralisation had been noted since the 1890s near the Borroloola region of the central eastern side of the NT, but it was not until the mid-1950's that modern mineral exploration began to explore the southern end of the geological McArthur Basin in this area—with geologists working for Mt Isa Mines Ltd ('MIM') discovering the Pb–Zn mineralisation at the "Here's Your Chance" (HYC) ore body in late 1955 (Logan *et al*, 1990). Initial MIM studies of the HYC deposit showed that it contained extremely fine-grained mineralisation, with good Zn grades—but technology of the time could not process the ore to recover the Pb–Zn efficiently. Despite ongoing exploration and a major feasibility study in the late 1970's, the giant size of the deposit could not overcome the basic technical issues, these reduced economic viability and the project remained stalled. By the early 1990's, however, new developments in fine grinding technology, especially the new IsaMill grinding technology (Fountain, 2002; Rossberg & Pafumi, 2013), allowed a bulk concentrate to be extracted from the ore—although this was only able to be sold to a limited number of smelters around the world (namely those using Imperial Smelting Furnace technology). In the early 1990's, MIM underwent an environmental impact assessment (EIA) process for the project, gaining approvals and development began in 1994 with site commissioning in May 1995—by late 1995 the McArthur River project was in full-scale commercial production and processing at a rate of about 1.6 million tonnes per year (Mt/year). The project was developed as a joint venture with MIM holding 70% and a Japanese consortium of Nippon, Mitsui and Marubeni holding 30%.

In its initial two years of operations (the 1995/96 to 1996/97 financial years) the McArthur River project made a significant financial loss, forcing MIM to examine ways to make the site profitable in the prevailing economic environment (MIM, var.-a). This was compounded by underground mining being more difficult than originally envisaged, with poor ore recovery from stopes, ore dilution and difficult ground conditions causing concerns about stability and rockfalls (Stewart & Gwynne, 1998). Investments in various mine productivity initiatives (to address the issues just noted), saw profitability achieved in the 1997/98 financial year and by 1998/99 "problems encountered with the start up of McArthur River Mine's (MRM) performance have now been overcome" (p. 21, 1999 Edition, (MIM, var.-a). Financial statements reported this turnaround with the financial year 2000 showing an "exceptional result" of $23.4 million profit from $183.9 million of sales—almost double that of Mount Isa's profits of $12.0 million from $412.2 million of revenue (p. 16–17, 2000 Edition, (MIM, var.-a). By 2002 McArthur River was again making losses, but this was overshadowed in mid-2003 by the takeover of MIM by new global mining company Xstrata plc[2]. Around the same time, nearly half of the world's Imperial Smelters had closed (5 out of 12), meaning higher costs for the McArthur River project and again placing the project in a difficult financial position (e.g. 2003 Edition, (Xstrata, var.-a). Various proposals were considered to return the project to profitability, including an onsite Zn refinery with a 350 MW power station and converting to a large open cut scale (4.8 Mt/year) (Rossberg & Pafumi, 2013; Warner, 1998). Despite little public justification, the final option chosen in 2005 was to convert from the underground to an open cut operation, requiring a 6 km long diversion of the McArthur River itself (since the orebody goes underneath the project's namesake river) as well as slightly expanding milling capacity (to 1.8 Mt/year) with improved processing technology. Xstrata also bought the remaining 30% in September 2005 to take full control of the McArthur River project.

An EIA process was undertaken for the proposed open cut project to obtain all relevant NT and Commonwealth approvals, with the main environmental impact statement (EIS) released in August 2005 (URS, 2005). The proposal raised significant controversy, especially relating to indigenous heritage and environmental risks—although a pilot or 'test' pit had already been approved in July 2005 by the NT Department of Primary Industries, Fisheries and Mines (NTDPIFM) prior to the release of the EIS and public consultation phase of the EIA process. In February 2006 the NT Environmental Protection Agency (NTEPA) recommended rejection of the project. Despite this and to avoid MIM reducing their workforce and potentially closing the mine, special approval was given by NTDPIFM to expand the test pit in April 2006. At the same time another EIA process was begun to assess the open cut expansion project again—this time through a public environment report (PER—a "mini" or reduced scope EIS) released in July 2006 (URS, 2006). The NTDPIFM and NT Government approved the PER in October 2006, closely followed by relevant Commonwealth EIA approvals. The underground mine was permanently closed in April 2016.

Significant opposition to the project and approval process resulted in the Borroloola region Traditional Owners initiating legal proceedings, firstly in the NT Supreme Court in December 2006, then with additional

2 Xstrata plc was a UK-listed company with mainly Swiss origins and South African assets but with a major stake owned by natural resources trading company Glencore International AG.

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proceedings in the Commonwealth Federal Court in February 2007. On 30 April 2007, the community won the case in the NT Supreme Court and the approval of open cut expansion was ruled invalid. This ruling was strongly criticised by the then NT Chief Minister, Clare Martin, who announced on 2 May 2007 the Labor Government would pass legislation to over-ride the court's decision—this was completed amidst intense political controversy on 4 May 2007, just five days after the Supreme Court's decision. This lead to a historic point in NT politics with three indigenous members (Malarndirri (Barbara) McCarthy, Alison Anderson and Karl Hampton) crossing the floor to vote against the bill whilst the Environment Minister, Marion Scrymgour, and the Shadow Minister for Mines, Fay Miller were both absent from the chamber when the vote was taken (Howey, 2010; Young, 2015).

The Federal Court process included an injunction sought to prevent the diversion of the McArthur River, this was rejected on the 13 May 2008, with the final decision one month later also finding against the communities' case on 13 June 2008 (Howey, 2010). This decision was appealed by community representatives and won on 17 December 2008, stopping work on the open cut—although the McArthur River itself had already been diverted for the 2008/09 wet season (and the mill kept running on stockpiled ore). This forced Xstrata to quickly resubmit documentation for a new determination in mid-January 2009, which was given conditional approval by the new Labor Minister for the Environment, Peter Garrett, on the 20 January 2009 and included a 10 day public consultation period—by 20 February 2009 the project had been approved (again). Work resumed in the open cut and operations settled into a normal routine.

A unique outcome of the two 2005–2006 EIA processes and subsequent political manoeuvring was a number of conditions, including ***"… a substantial environmental bond, a properly researched and managed program for revegetating the river, proper management of contaminants from the mine site and tailings facility well beyond the projected life of the mine, the establishment of a mine funded monitoring and regulatory agency and a legal agreement or legislation to provide social benefits for the Gulf community"*** (Young, 2015 p.4). This resulted in the mine funding an 'independent monitor' to take and test samples and publicly report on the environmental impacts of the project, with the process managed by the NT Government. A consultant was to be appointed through a tender process and was expected to provide neutral, objective testing and analysis of the McArthur River project—an extremely rare requirement for mining projects across Australia.

The mine sought additional environmental approvals in March 2011 to expand the production rate (up to ~5.5 Mt/year), undertaking another EIA process and releasing a major EIS in February 2012 (URS, 2012)—with the NT Government approving this latest expansion of McArthur River in June 2013. A unique aspect of this expansion was the inclusion of a new processing circuit to allow the production of a separate Zn concentrate along with the normal bulk Pb–Zn concentrate—made possible by recent advances in milling technology.

By the end of 2015, the project has processed about 37.1 million tonnes (Mt) of ore, at grades of 5.0% Pb, 11.8% Zn and about 50 g/t Ag, to produce about 0.75 Mt Pb, 3.3 Mt Zn and 885 t Ag (i.e. 28 million ounces Ag) (data updated from (Mudd, 2009b). Unfortunately, Xstrata–

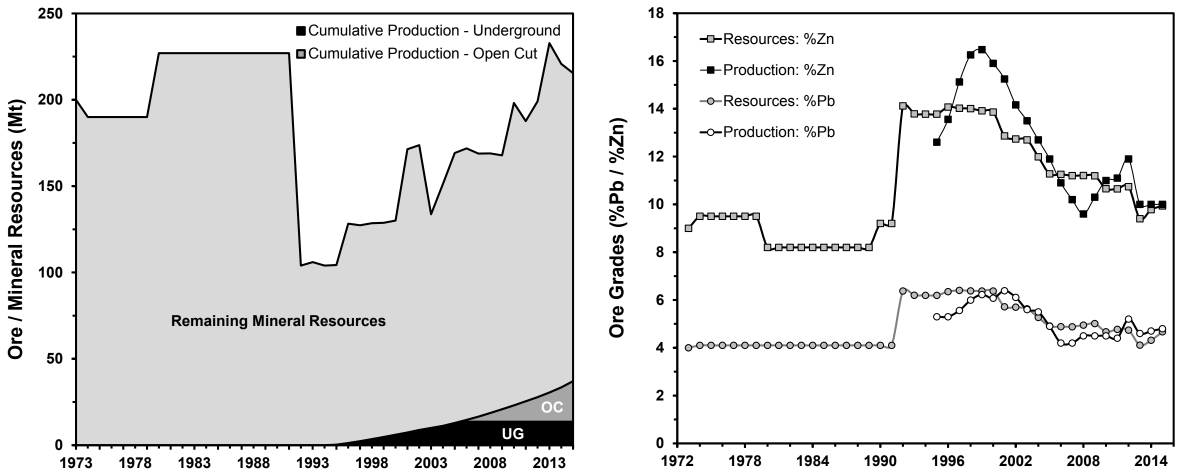

Figure 1: Historical mining data for the McArthur River project: (left) remaining mineral resources and ore milled by underground or open cut; (right) Pb–Zn ore grades for remaining mineral resources and ore milled (data sourced from (Glencore, var.-a, b, c; MIM, var.-b; Mudd, 2009b; Xstrata, var.-b, c)

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Glencore did not report the extent of ore mined from underground mining versus open cut mining during the transition from 2005 to 2009, nor has there been any reporting of the extent of waste rock mined during the project (see (Glencore, var.-a, c; Xstrata, var.-a, c, d, e)[3]. As of December 2015, the project still has a remaining mineral resource of 178.3 Mt at 4.7% Pb, 9.9% Zn and 48 g/t Ag, containing about 8.3 Mt Pb, 17.7 Mt Zn and 8,504 t Ag (or 273 million ounces Ag) (Glencore, var.-b)—showing that the project, at ~5.5 Mt/year, still has the potential to be mined for at least another thirty years.

Based on the 2005 EIS (Table 4.2, p. 4–4) and the 2012 EIS (Table 4–6 & 4–7, p. 4–17/18), it is possible to estimate the extent of waste rock mined at McArthur River based on the 'strip' ratios—simply the waste rock divided by ore mined. Depending on the stage of the open cut, the strip ratios vary from 2.8 to 6.4 over the period 2006 to 2029 and average about 5.6 (Phase 3 value). The approximate waste rock mined per year from the open cut is given in Figure 2 (there is no waste rock from underground mining since this is disposed of in former underground mine voids; see section 7.1 (URS, 2005)—a cumulative total of ~173.6 Mt of waste rock.

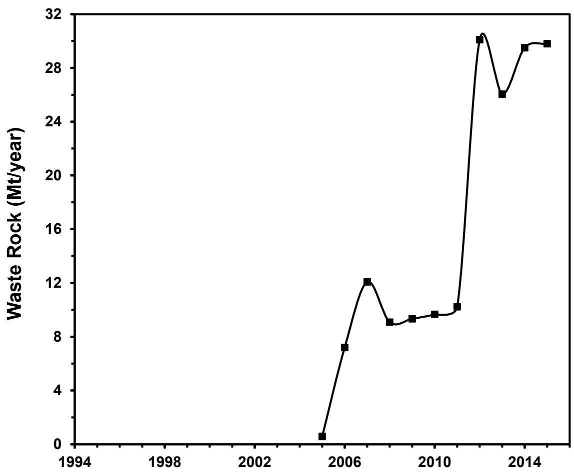

Figure 2: Estimated annual waste rock mined at the McArthur River open cut (data calculated from production data above and strip ratios from Table 4.2, (URS, 2005)

Through the Independent Monitor a variety of major environmental issues and risks have become apparent (see EES, 2009, 2010, 2011, 2012; ERIAS, 2014, 2015)—such as tailings seepage into surface waters and groundwater, acid mine drainage (or AMD; explained in more detail later), as well as the potential for heavy metals to be accumulating in biodiversity near the mine. In early 2015, these concerns were amplified by the fact that the northern waste rock dump appeared to be 'on fire' due to the large plumes of smoke emanating from the dump. This is closely related to AMD, since the geochemical reactions occurring to form AMD also generate significant excess heat. It is well known in the mining industry that unrehabilitated waste rock dumps undergoing the generation of AMD can reach internal temperatures of 60–80° C (e.g. Blowes *et al*, 2014)—meaning that the waste rock dumps at McArthur River are 'cooking' the rocks and causing smoke. Whilst it is relatively rare in mining that AMD processes lead to this outcome, it is an issue that has long been recognised given the pervasiveness of AMD problems across the mining industry. For example, the elevated temperatures caused by AMD in organic-rich shales at iron ore mines in the Pilbara was causing uncontrolled and early detonation of explosives—leading to different mine planning and major changes in mine waste management of such materials (see Porterfield *et al*, 2003).

Although the McArthur River site put substantial work into the reduction and prevention of the smoke generation, further reports of smoke emanating from the site emerged in early August 2016[4] but this time from the relatively new southern waste rock dump (not shown in Figure 3).

The public health consequences and obvious environmental implications of such significant AMD risks led to a new EIA process being initiated in June 2015, although the EIS has yet to be publicly released.

Recent aerial views of the project area are shown in Figures 3 and 4.

There is therefore a clear need to examine possible long-term scenarios for the McArthur River project, and especially the short-term management of waste rock but critically the suitability of leaving such reactive mine wastes above ground in perpetuity—i.e. forever.

3 Although subsequent Xstrata sustainability reports aggregate their Australian zinc operations for one report, the total waste rock reported therein is across all Mt Isa sites as well as McArthur River and no specific data for McArthur River is provided (except tailings) (see Xstrata, var.-d). It is most unfortunate that since the takeover of Xstrata by Glencore (~2012) that no more sustainability reports have been published.

4 Sara Everingham, "Waste rock could be burning again at McArthur River Mine." Australian Broadcasting Corporation (ABC), 5 August 2016, www.abc.net.au/news/2016-08-05/waste-rock-could-be-burning-again-at-mcarthur-river-mine/7696024

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Figure 3: Recent aerial perspective view of the McArthur River project area (supplied by Borroloola community)

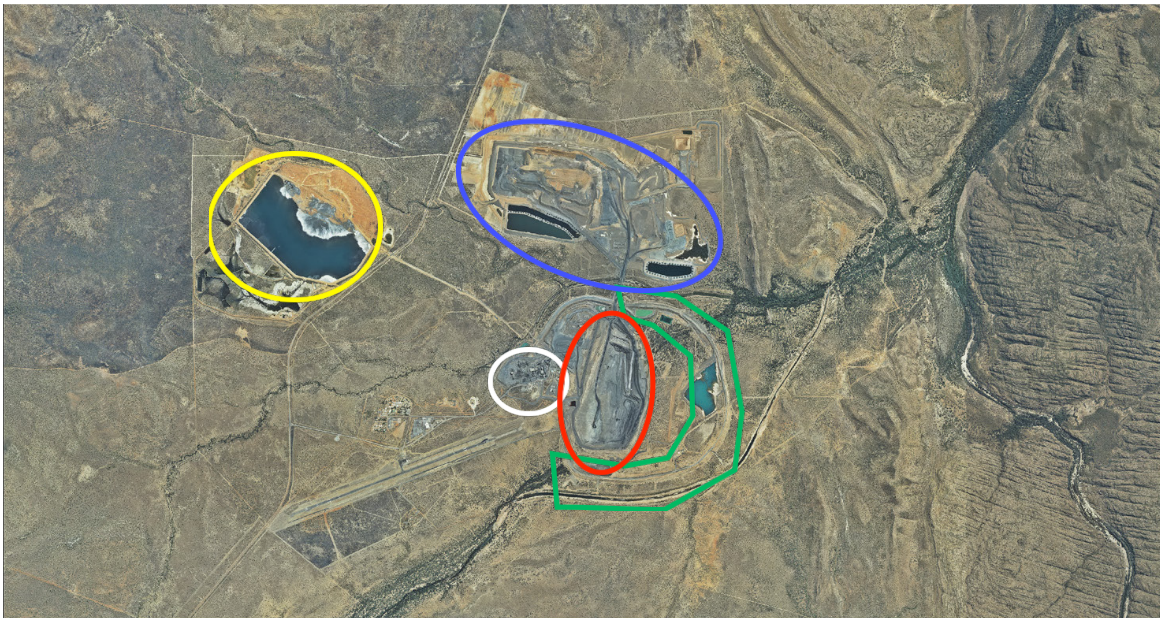

Figure 4: Aerial view of the McArthur River project area, showing the open cut (red oval), northern waste rock dump (blue oval), tailings dam (yellow oval), process plant (white oval), McArthur River diversion and bund wall (green outline) (adapted from Figure 1.2, (ERIAS, 2015)

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ACID MINE DRAINAGE: A BRIEF OVERVIEW

BACKGROUND

> *"… 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 of Saxony in eastern Germany, initially a medical doctor, later a scholar of mining[5] and widely recognised as one of the founders of the modern mining industry, is stark recognition of acid and metalliferous drainage—more commonly known as acid mine drainage or 'AMD'. In other words, AMD has long been acknowledged as a major environmental (and social) problem—the principal difference between Agricola's era and now is the massive global scale of mine wastes and associated AMD issues (amongst many others, such as erosion, groundwater, ecosystem re-establishment, visual amenity, social impacts, etc.).

In mining, both tailings and waste rock can present major AMD risks. Due to growing metal demands and declining ore grades, and especially the rapid expansion of open cut mining, the mass of mine waste produced annually by the global mining industry is of the order of several tens of billion tonnes (or more) and growing rapidly every year (e.g. Franks, 2015; Mudd & Boger, 2013; Spitz & Trudinger, 2008). 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 deposited using a slurry pipeline into valley fill or ring dyke structures commonly called tailings dams or tailings storage facilities (or TSFs). Either approach presents various risks, depending on complex factors (especially climate and geographic issues), with some examples of TSF disasters include Mufulira (1970, copper), Bafokeng (1974, platinum), Los Frailes (1998, zinc), Baia Mare (2000, gold), Kolontár (2010, red mud), Mount Polley (2014, copper–gold) or most recently Samarco (2015, iron ore)—all having major environmental impacts and/or loss of life. A widely cited quote, attributed to the US Environmental Protection Agency from 1987, states:

> *"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"*
> (Note: the primary US EPA source/report for this quote is unknown; it is cited by (EEB, 2000)

In a similar vein, the industry-funded 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 front page of www.inap.com.au[6]).

A perhaps ironic curiosity of global mining history is the name-sake mine which the British Rio Tinto company operated in the Tinto region of southern Spain from the 1870s to the 1950s—a region renowned for lead and copper mining from Roman times—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 for more than a millennia—Rio Tinto even made use of the AMD in large piles of ore to leach the copper out cheaply for great profit, a process now called heap leaching. Hence it cannot be claimed that AMD was never understood, it's just that the often severe environmental impacts from AMD were explicitly ignored. 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. Given the vast scale of accumulated mine wastes globally, AMD is a significant and growing global problem.

A BRIEF OVERVIEW OF AMD

At its simplest, the biogeochemical[7] processes which lead to AMD are the exposure of various iron sulfide minerals in mine wastes to oxygen and water, typically due to the mining and exposure of iron sulfides to the surface environment—allowing the sulfide to convert to sulfuric acid and the iron to an iron oxy-hydroxide (or just iron hydroxide), with the overall process called sulfide oxidation. The most common iron sulfide minerals involved in AMD are pyrite (FeS_2) and pyrrhotite ($Fe_{1-x}S$), although others may also be involved (eg. arsenopyrite, chalcopyrite). Although there are many possible stages in the formation of AMD, including the action of microorganisms (e.g. Blowes *et al*, 2014; Dold, 2014), the overall biogeochemical process can be explained by the following simplified equation (e.g. Lottermoser, 2010; Taylor & Pape, 2007; Verburg, 2011):

5 Agricola, noting the high incidence of disease in his patients who worked in mining, became more interested in the basics of mining and changed career to focus on mining and metals.

6 Last accessed 12 August 2016.

7 Biogeochemical is simply the combination of biological, geological and chemical processes.

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

(or in words):
pyrite + oxygen + water → iron oxy-hydroxides + sulfuric acid + heat

In other words, for every bit of pyrite (or similar sulfide) it takes a significant amount of water and oxygen to produce iron oxy-hydroxides (a solid rust-like precipitate), sulfuric acid and energy in the form of significant heat. The acid in turns dissolves a range of heavy metals and salts, creating a drainage chemistry which is invariably very toxic to aquatic ecosystems—as already observed by Agricola centuries ago (and others before him). Visual examples of AMD sources and impacts on streams are shown in Figure 5.

Figure 5: Examples of acid mine drainage from around Australia: (top to bottom, left to right) AMD affected stream, former Sunny Corner Pb-Ag mine, NSW (14 July 2013); AMD affected urban drain, Zeehan Pb-Ag mining field, TAS (13 February 2014); AMD in seepage drain from the rehabilitated tailings dams of the former Captain's Flat Pb-Zn-Ag-Cu-Au mine, NSW (3 July 2015); Dee River, ~10 km downstream of the former Mt Morgan gold-copper mine, QLD, nearby public warning sign (inset; 25 Sept. 2012); AMD-affected retention ponds from the former Tabletop gold mine, QLD (25 June 2011); AMD-affected groundwater entering open cut, former Redbank Cu mine, NT (26 June 2011)
(all photographs by the author, except bottom right by Jessie Boylan/MPi)

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In reality, the biogeochemistry of AMD is highly complex, and depends on a wide variety of factors such as mineralogy, grain or particle size, climate (especially hydrology and temperature), mine waste geochemistry and management, moisture behaviour in mine wastes, microbiology and sometimes trace element substitution (see Blowes *et al*, 2014; Dold, 2014).

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 due to the action of microorganisms;
- *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 & 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.

INDUSTRY APPROACHES TO IDENTIFICATION AND MANAGEMENT OF REACTIVE SULFIDIC WASTES

Since the rise of environmental assessment processes and more stringent regulation in the 1970s, the mining industry has gradually increased their focus on how to identify and manage AMD risks, especially during initial assessment and approvals processes but also during operational practices. Over the past 20 years in particular there have been a range of guidance handbooks and reports prepared (e.g. INAP, 2010; Johnston & Murray, 1997; Parker & Robertson, 1999; Taylor & Pape, 2007), all outlining common approaches to identifying the extent of possible AMD risks and how to manage mine wastes during mining, site closure and rehabilitation to ideally prevent, or, at the very least, minimise long-term environmental risks to levels acceptable to regulators and local communities. In addition, there have been important academic contributions in monographs, conference and journal papers, textbooks and the like (e.g. (Blowes et al, 2003; Dold, 2014; Lottermoser, 2010; Nordstrom & Alpers, 1999; Spitz & Trudinger, 2008; Verburg, 2011)—amongst an increasingly wide array of literature now available on AMD.

- *Identification*—a comprehensive range of tests are available to assess the potential for AMD from mine wastes. Rock samples can be tested for their mineralogical content, such as sulfides or alkali minerals, and these accounted for in terms of the extent of acid potential versus alkali neutralising capacity (i.e. acid plus alkali gives a salt plus water)—this is known as acid-base accounting and leads to the 'net acid production potential' (NAPP), where a positive value indicates acidic potential and negative suggests acid neutralisation. Samples can also be subjected to leaching in a laboratory, and where a chemical is used to accelerate the potential AMD process (e.g. hydrogen peroxide), this is referred to as a 'net acid generation' (NAG) test. Tests of individual samples are known as 'static' tests. Another approach is to subject a reasonable mass of rock (or mine wastes) to water and surface conditions, such as large columns or humidity cells which can mimic the field conditions of a mine site, these are known as kinetic tests and can be conducted in the laboratory or the field. Tests involving large samples being tested over time are known as 'dynamic' or 'kinetic' tests. The use of geochemical models can also be a useful approach in assessing potential AMD risks. Overall, it is important to understand the strengths and weaknesses of all approaches, as AMD biogeochemistry is invariably complex and not always easy to predict with accuracy—hence a large program involving static and kinetic tests in combination with geochemical modelling is considered good practice.
- *Mine Planning & Operations*—Assuming mine wastes are correctly identified for their AMD potential, a mine can plan their operation to sequentially mine in a way which allows direct management of mine

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wastes and associated AMD risks. Most commonly, this involves the segregation of AMD wastes and their emplacement inside non-AMD producing wastes, as shown in Figure 6. Importantly, it is critical to constantly sample and test mine wastes throughout a projects' life. Finally, it is important to ensure that a comprehensive water management plan is in place which links AMD potential to seepage pathways, surface or mine water runoff ponds and the site water balance, as there may be a need to treat waters to ensure relevant environmental objectives and regulatory requirements are met.

- *Rehabilitation*—to limit AMD in the first place, engineering approaches typically aim to limit the availability of water, oxygen or both to underlying mine wastes. In wet climates, due to the low solubility of oxygen in water, an engineered water cover may be realistic, such as leaving permanent wetlands or ponds over reactive mine wastes. In dry climates, it may be possible to aim for engineered soil covers which shed water away from the underlying mine waste through surface runoff and limit the infiltration of water. In climates in between these extremes, careful consideration needs to the rehabilitation design of covers for waste rock dumps and tailings dams, to limit the intermittency of water and oxygen influxes to mine wastes, as this can be an ideal way to maximise AMD.

MCARTHUR RIVER AND MANAGEMENT OF REACTIVE SULFIDIC WASTES

By the end of 2015, the McArthur River project had generated approximately (~) 27.5 Mt of tailings and ~173.6 Mt of waste rock—although exact tailings and waste rock data has never been published or made available by the site (despite repeated requests to the company and NT regulator by or on behalf of the Borroloola and NT communities). Although the McArthur River project appears to manage its mine waste in a manner consistent with current industry practice (as per previous sub-sections)—that is, waste rock is placed in engineered dumps while tailings are pumped as a slurry for disposal in an engineered storage dam (or TSF)—there appears to have been something gone seriously wrong with the identification of AMD potential given the emergence of smoke plumes from the waste rock dumps and increasing concerns raised by the Independent Monitor of AMD issues and related water quality problems in mine water management. This is further discussed later in this report.

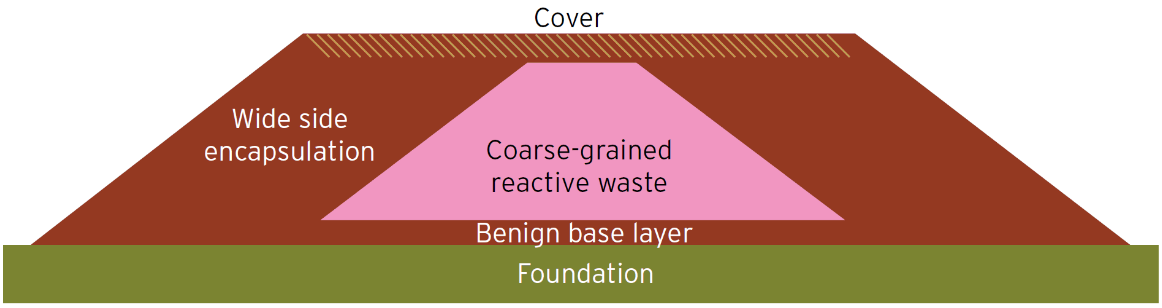

Figure 6: Conceptual plan for emplacing potential AMD (reactive) wastes inside non-acid forming mine wastes (Taylor & Pape, 2007)

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ENVIRONMENTAL IMPACT ASSESSMENT (EIA) HISTORY AND PREDICTED OUTCOMES

As noted above, the McArthur River project has gone through four major EIA processes in its ~25 years of developments to date. This section briefly notes the key risks and predicted outcomes from the various EIA processes—but focuses only on issues related to mine wastes (tailings and waste rock) and associated AMD risks and final site rehabilitation.

1992 EIS

Although the original 1992 EIS was not available for this report, the EIA Assessment Report was (CCNT, 1992). Key findings and issues identified include:

- *Waste Rock Management*—although the recognition of AMD risks was clear and the proposed method of encapsulating acid-producing rocks within alkaline rocks (such as dolomite) was accepted due to the greater abundance of dolomite compared to acid-generating wastes, it was also recognised that there was a lack of sufficient quantitative data to assess long-term risks. Finally, as the mine was underground, the extent of waste rock was very small and was expected to be emplaced back in the underground workings as the mine progressed and voids became available for such disposal—thereby minimising this major environmental risk.
- *Tailings Management*—the tailings were to be discharged as a slurry into a storage facility (or 'tailings dam') and, due to the very high evaporation rate of the region, would dry and form a stable structure—although there was uncertainty given the lack of experience with this approach. The tailings were recognised as potentially acid-forming, but there was uncertainty over the speed of the potential acid formation. Finally, although the tailings were expected to produce a dry, stable mass which limits the potential for seepage (due to the lack of water to seep), the uncertainty regarding tailings water management—especially whether the tailings would indeed dry out—meant that seepage risks from the tailings dam remained of significant concern.
- *Rehabilitation*—the plans for eventual site rehabilitation were "… not well documented, in particular those for the waste rock dump and the tailings impoundment" (CCNT, 1992 p.19). Although five options were presented, they effectively lacked technical detail matched to local site conditions—meaning significant future work was required.

2005 EIS

The management of tailings and waste rock was discussed in detail in Section 7 and mine rehabilitation in Section 20 of (URS, 2005), with key findings and issues including:

- *Waste Rock Management*—based on detailed geochemical studies in 2002, waste rock was classified (Table 7.1) as non-acid forming (NAF) or potentially acid-forming (PAF), with the dominant rock types being Upper Pyritic Shale (47% PAF), Lower Pyritic Shale–Bituminous Shale (13% PAF), Lower Dolomitic Shale (not PAF), W-Fold Shale (not PAF) and Teena Dolomite (not PAF). Based on the final open cut mine plan and some 183 Mt of waste rock, **it was expected that only 11% would be PAF whilst 89% was NAF** (Table 7.2). As outlined

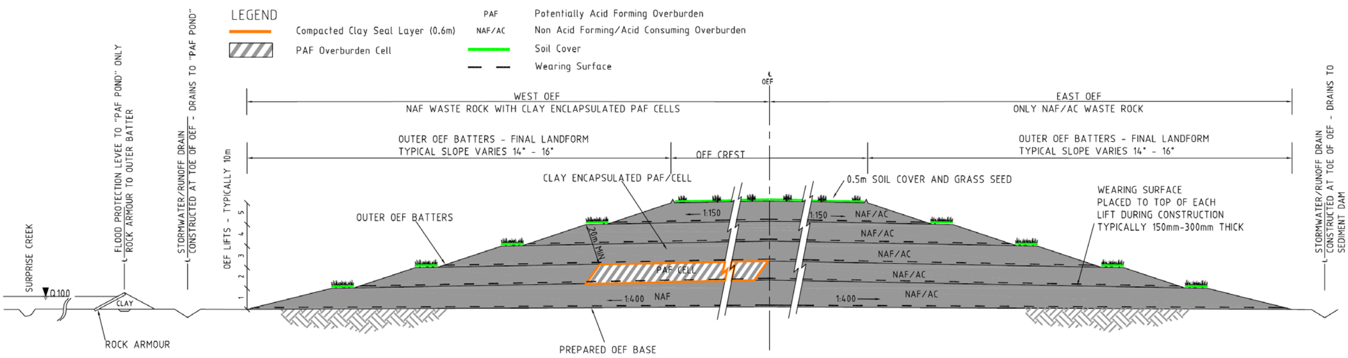

Figure 7: Schematic of encapsulating potentially acid forming (PAF) waste rock within non-acid forming (NAF) waste inside the 'overburden emplacement facility' (OEF) (adapted from (URS, 2005)

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previously (sub-section 4.2), approaches proposed by the project included detailed geochemical testing ahead of mining to identify waste rock as NAF or PAF, encapsulation of PAF wastes within NAF wastes, careful engineering of base liners beneath waste rock dumps, seepage collection and water management systems. The waste rock dump was proposed to the north of the pit, and was named the 'overburden emplacement facility (OEF). A schematic is shown in Figure 7. There is no discussion of previous management practices versus actual outcomes.

- *Tailings Management*—tailings would continue to be slurried to and deposited in the tailings dam to the west of the mill and mine, and extended into the area used for evaporation and water management. There is considerable discussion of tailings dam design, associated water management practices (especially water quality), seepage models and the fact that seepage was first observed in Surprise Creek from the tailings dam in June 1997 (i.e. about 2 years after operations began), and discussion of the closure and rehabilitation of the first cell of the tailings dam (the main dam associated with underground operations). Although there is detailed discussion of seepage issues from the tailings dam, due mainly to areas of permeable sandy/gravelly lenses, there is no explicit discussion of how the tailings have dried (or not as the case appears to be). Similar to waste rock, there is no detailed discussion of previous management practices versus actual outcomes (except perhaps that seepage was somewhat unexpectedly found to occur).

- *Rehabilitation*—various aspects of site closure and rehabilitation were discussed and adopted, including site infrastructure (roads, mill, power station, accommodation camp), waste rock dumps (OEF) and tailings dam cells. In essence, site infrastructure would be removed and/or isolated while mine wastes would be rehabilitated by placing engineered soil covers to limit infiltration, seepage and long-term AMD risks and all areas would be revegetated. A range of qualitative criteria commitments are presented, with post-mining land use, after consultation with stakeholders, expected to be low intensity cattle grazing. Curiously, there is no mention at all in Section 20 of any rehabilitation of the ~6km diversion channel of the McArthur River and long-term risks of flooding to the site, especially any risks of flooding the open cut—implying that this was not considered important to assess.

2006 PER

The management of tailings and waste rock were discussed to varying levels of detail in Sections 2, 3, 6 and 7 (URS, 2006), whilst mine rehabilitation was not assessed at all, with key findings and issues including:

- *Waste Rock Management*—Section 6.2.1 notes briefly that all overburden (mine waste) materials have been tested and classified as either NAF or PAF, with "11% of the total overburden could be PAF" (p. 6–2) and will be managed accordingly (i.e. as per the previous EIS and industry practice for AMD as reviewed in section 3.3 of this report). Results are also presented of further kinetic testing (Table 6.1) being undertaken to further study AMD risks from overburden materials. The potential for in-pit disposal of waste rock was recognised as beneficial (section 3.4.2) but argued as impractical during operations given the design of the open cut (i.e. limited opportunity due to the ongoing nature of mining in all areas of the pit).

- *Tailings Management*—similar to the 2005 EIS, tailings would continue to be slurried to the TSF, with extensive design aspects used to limit seepage rates, such as compacted clay, geopolymers and the use of groundwater bores to pump seepage back to the TSF. The seepage problems of the main TSF (or cell 1) are acknowledged, and it is proposed to close and rehabilitate this section of the TSF. The need to manage water within the TSF to limit sulfide oxidation is also acknowledged. Finally, a detailed rehabilitation plan for the TSF is presented and discussed, mainly placing an engineered soil cover system over the TSF to isolate the tailings and achieve a stable landform for the long-term.

2012 EIS

The management of tailings and waste rock and mine rehabilitation were discussed in detail in Sections 3 and 5 of (URS, 2012), with key findings and issues including:

- *Waste Rock Management*—there is a recognition of PAF mine wastes, and that these need to be isolated and that such wastes are currently successfully isolated within clay lined cells surrounded by NAF materials (sub-section 3.4.10). In this section, it is explicitly acknowledged that engineered soil cover systems are far from ideal in isolating PAF wastes in perpetuity, as the approach adopted at

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McArthur River would **"… eliminate the long-term cover failure risks associated with traditional PAF OEF design: cover erosion, surface runoff ingress, localised cover failure through deep rooted trees, burrowing animals and uprooting of trees in storm events"** (URS, 2012 p. 3–14). The additional waste rock expected to be mined under the Phase 3 expansion totalled 525.8 Mt, adding to the 131.5 Mt already allowed for from the 2005/06 EIA processes for Phase 2 (or the original open cur approvals) (Table 4–6. (URS, 2012).

- *Tailings Management*—expansion of TSF scale but largely a continuation of current practice with no significant changes from the 2005 EIS.
- *Rehabilitation*—although various options for the final open cut were considered (e.g. redirecting the flows temporarily or permanently from the diversion channel to the pit), the preferred option was to allow the open cut to fill naturally with no link the diverted McArthur River. It was acknowledged that this scenario would lead to declining water quality (i.e. brackish to saline water) in the pit over decades to a century. A variety of design criteria or principles were presented for the TSF and OEF's (e.g. slope angles, 20 m of NAF wastes surrounding PAF wastes by the end of OEF construction, landform stability, revegetation, etc.), although there was minimal detail of AMD risks in the main EIS volume—with the technical detail left to specific appendices (e.g. E1–E2).

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INDEPENDENT MONITOR REPORTS

The process of appointing an 'independent monitor' (IM) to take samples and assess the environmental impacts of a mining project is very rare in Australia—with the only other prominent example of such close environmental scrutiny being the Ranger uranium mine (in the Kakadu region of the Northern Territory; e.g. Ferguson & Mudd, 2011; Mudd, 2008). Since it's beginning, the IM of the McArthur River project (or 'MRIM') has been able to assess the extent to which the mine is meeting its environmental requirements and provide an independent perspective on its impacts.

Although there are several substantial reports now published by the MRIM (EES, 2009, 2010, 2011, 2012; ERIAS, 2014, 2015), this report will focus on the most recent report as the basis for the current state of affairs for the McArthur River mine and its environmental risks and issues.

Overall, the MRIM has shown consistently that despite many environmental management requirements being met, major gaps remained and that these risks were escalating. By the 2014 period of reporting by the MRIM (ERIAS, 2015), the increasing AMD risks were identified as the ***"most significant environmental issue at McArthur River mine" (p. ES-1) and that "management of overburden remains the single largest issue which has implications for both the short- and long-term environmental performance of the site"*** (p. ES-2). Importantly, specific issues or concerns identified by the MRIM include:

- Potential AMD risks in the southern OEF facility;
- The lack of reported waste rock data, especially the balance of PAF and NAF materials, with the MRIM's best estimate being that only 9% was NAF (in stark contrast to the 2005 EIS estimate of 89% of waste rock being NAF, as noted earlier)—**or, in reality, meaning that some 91% of waste rock was PAF waste**;
- Quality control issues in the construction of the OEF facilities and the clay liners used to isolate PAF wastes—including testing and inspection regimes;
- TSF management, including incident management, inspection processes, and flooding capacity of Cell 1 (the main TSF area used for the first decade or so before the open cut expansion);
- Escape of heavy metals into the environment around the Barney Creek haul road bridge via sediment, dust and/or surface runoff;
- The complex and sometimes lengthy time required by the primary NT regulator, the Department of Mines & Energy (NTDME), to assess and approve critical operational documents—especially the Mining Management Plan (MMP) as required by NT mining legislation—this was ending in confusion between approved activities from the 2012 Phase 3 EIS and those intended for the expected overburden management EIS due to be completed and released soon.

As a contrasting example, the Cadia Valley operations of Newcrest Mining Ltd report annually their waste rock but also the split between NAF and PAF, as shown in Figure 8. A good feature of NSW mine regulation is that companies are required to make annual environmental monitoring and management reports publicly available on their own mine-specific websites—and NSW remains the only state in Australia to require this. This allows greater transparency on the results from monitoring and potential mine-related impacts, but also shows that parts of the mining industry recognise the need to address AMD risks publicly as part of such statutory requirements to address public concerns.

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13.1 WASTE ROCK AND TAILINGS MANAGEMENT

13.1.1 Material Characterisation

Cadia Hill waste rock is classified into three different waste types depending on its mineralisation and sulphur content. The three classifications are Blue, Green and Pink representing Non Acid Forming (NAF) Waste, Mineralised Waste and Potentially Acid Forming (PAF) waste respectively. Waste type is colour coded to simplify the day-to-day Load and Haul operations (Figure 13-1). This classification scheme is the same as has been reported in previous AEMRs.

Waste rock is sampled and classified on the basis of the sulphur (S) content. A 0.5% sulfur cut-off grade is used. Classification is based upon the estimated grade of each modelled block (1 block is 12.5m x 12.5 m x 15m (bench height). The sulphur grade for each block is estimated by spatial modelling of the waste material, using a statistical process known as ordinary kriging. Ordinary kriging uses a weighted assay estimate based on a graph known as the geostatistical semi-variogram. All blocks with an estimated sulphur grade above 0.5% S are classified as PAF. Additionally, where there is a demonstrable geological cause, e.g. a “g-fault” is identified, material with a lower sulphur cut-off may be classified PAF.

13.1.2 Waste Rock Emplacement

13.1.2.1 Cadia Hill Gold Mine

Approximately 13.65 Mt of in-situ material was mined from Cadia Hill pit during the reporting year. This amount consisted of approximately 11.9 Mt of ore, 1.44Mt of low grade material (yellow) and 281Kt of waste rock. Most waste mined was placed in the South Waste Rock Dump; consisting of 0.155 Mt of mineralised waste (Green), 3Kt of PAF waste (Pink) and 0.123Mt of NAF waste (Blue) Approximately 1.22Mt of ore was reclaimed from stockpiled for feeding through the primary crusher.

Figure 8: Waste rock section of the 2010/11 environmental monitoring and management report for the Cadia Valley operations of Newcrest Mining Ltd in NSW (combined from pages 140–141, Newcrest, 2012) (note: the Cadia Hill pit was close to care and maintenance during this time, with earlier years showing greater volumes of waste rock mined and classified)

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CONCEPTUAL SCENARIOS FOR THE LONG-TERM FUTURE OF THE MCARTHUR RIVER MINE

THE CASE FOR COMPLETE PIT BACKFILL

The very nature of sulfide oxidation in mine wastes (i.e. AMD) at modern mines means that the environmental and related risks need to be considered very differently to historic approaches—due to the long time frame over which AMD can continue (up to millennia), the increasingly large to massive scale of wastes involved, and the challenges in ensuring the integrity of site rehabilitation long into the future. This means that new approaches to minimising long-term environmental risks need to be implemented—and for large volumes of sulfidic mine wastes from modern mining, arguably the best approach is to place such wastes back into the former open cut, also known as pit backfill.

In general, it is very rare in the global mining industry to undertake complete backfill of mine wastes into a former open cut after the completion of mining—with the best examples being the former Flambeau copper mine (a small project in Wisconsin, USA, operating over 1993–97) and the currently operating Ranger uranium project, NT. There are also examples where a former open cut is used for the deposition of tailings (rather than expand an existing or build a new TSF), such as the former Nabarlek uranium mine, NT, some gold mines in the Tanami region, NT, and other gold mines in Western Australia (e.g. Fortnum) and Queensland (e.g. Kidston). Invariably, all of these examples were justified on cost and environmental grounds, and not directly due to long-term AMD risks. A unique case study where partial pit backfill was justified on AMD grounds was the former Woodcutters Pb–Zn–Ag mine, near Batchelor, NT, whereby sulfidic mine wastes were backfilled into the former open cut as part of site rehabilitation to minimise long-term AMD risks—this is summarised in more detail below.

The McArthur River site, given the major and ongoing AMD risks it is managing, also presents a strong example for the use of complete pit backfill. The principal technical arguments include:

- Sulfidic waste is below ground level and erosion of engineered soil covers is avoided;
- Sulfidic waste is below the water table, and given the low solubility of oxygen in water and the time it takes for oxygen to diffuse through the thick cover of mine wastes, this almost eliminates the availability of oxygen to drive the biogeochemical process of sulfide oxidation and AMD;
- Deep-rooted trees cannot penetrate through and compromise any engineered soil covers, since thick roots provide open pathways for the infiltration of water;
- Sulfidic waste is well below the zone where interaction with the above ecosystem would be important, such as tree roots and burrowing animals;

Some issues of pit backfill include potential groundwater quality impacts (especially if AMD is already occurring in mine wastes and there is migration of solutes from the mine wastes into the surrounding groundwater), major costs involved, and the expansion of volume in rock when it is blasted and mined—meaning that waste rock may occupy a greater volume than the original pre-mined rock and some sulfidic wastes may still sit above the post-mining groundwater table and be subject to oxidation and AMD risks.

Overall, it is important to consider all impacts and risks and contrast above ground rehabilitation of mine wastes with the costs and benefits of pit backfill, even if only partial.

There remains a dearth of studies which document such outcomes in modern mining—although there remain abundant case studies showing the ongoing pollution risks of leaving sulfidic mine wastes above ground in perpetuity (e.g. former mines such as Rum Jungle, Mount Lyell, Redbank, Mount Morgan, Captain's Flat, Teutonic Bore, Brukunga, amongst many others).

WOODCUTTERS CASE STUDY

The former Woodcutters Pb–Zn–Ag mine, about 100 km south of Darwin, operated from 1985 to 1999 and was a modest scale project involving open cut and underground mining. A total of 4.72 Mt of ore was processed, at grades of ~6.0% Pb, ~12.9% Zn and ~80 g/t Ag, and although no data is reported on the extent of ore mined by open cut or underground mining nor any associated waste rock data, it is estimated that only ~0.27 Mt was mined by open cut (Mudd, 2009b). The site had gone through various owners, mainly junior miners, until Australia's major gold miner Normandy Mining became site owner in the late 1990's—only to have America's Newmont Mining Corporation take over Normandy in early 2002, leaving Newmont to complete rehabilitation of the Woodcutters site (despite never operating the mine). The rehabilitation works are outlined by Taylor and Pape (2007) and Dowd (2005) and briefly summarised here.

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In 2000, Normandy commissioned detailed groundwater–surface water modelling studies to assess five scenarios for site rehabilitation from AMD risks, with the study showing that there was a clear need to relocate sulfide-rich tailings into the former open cut and backfill to a similar topography prior to mining as well as build engineered soil covers over the waste rock dumps to limit surface infiltration and AMD generation. Despite having no strict legal requirement to undertake such works for site rehabilitation, Newmont committed to this approach and all works were completed by 2004.

Curiously, although estimates of site rehabilitation in the 1980s were a mere $0.5 million, the final cost of all works by 2004 was ~$40 million. Aerial views of the site before and after rehabilitation are shown in Figure 9.

Figure 9: Aerial views of the former Woodcutters Pb–Zn–Ag mine, NT—(top) prior to rehabilitation in 1998 (Taylor & Pape, 2007); (bottom) recent site view 17 May 2016 (GE, 2016) (note: north is pointing to the right)

MCARTHUR RIVER

At present, the expected approach for eventual closure and rehabilitation of the McArthur River site is to leave tailings and waste rock above ground after engineered cover systems have been constructed and allow the former open cut to flood whilst leaving the diversion channel in place (e.g. 2012 EIS, as briefly noted previously). This is shown conceptually in Figure 10, including the main arrows for water flows. As explicitly acknowledged in the 2012 EIS (as highlighted previously), the site recognises that the use of engineered soil covers alone is insufficient to ensure protection into the long term—due to erosion of soil covers, burrowing animals and tree roots which can act to compromise the integrity of the cover and allow the ingress of water and oxygen into the underlying sulfidic wastes.

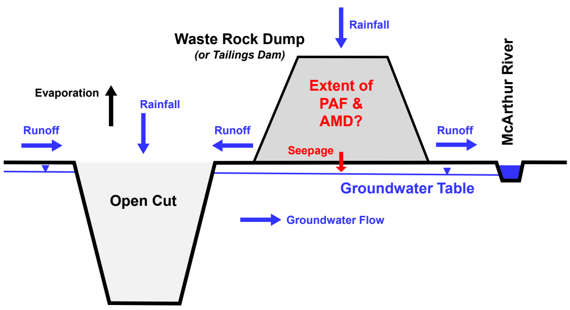

Figure 10: Conceptual representation of the McArthur River site after the end of mining

In all figures PAF wastes explicitly include both waste rock and tailings.

The current evidence at the site, however, is showing highly reactive wastes and that the vast majority of the waste rock is now (or probably should be) classified as PAF, as shown by the MRIM's assessments—meaning there remains deep concerns about the life-of-mine material balance to continue to isolate such PAF wastes within NAF wastes in the manner proposed in 2012 EIS.

As noted in the AMD overview, the primary approaches to preventing (at best) or (more realistically) minimising AMD generation involve isolation in water to reduce oxygen exposure, encapsulating wastes within acid-neutralising or NAF materials, or the use of engineered soil covers to limit water and/or oxygen ingress to the underlying sulfidic wastes.

However, given the current understanding of the material balance at McArthur River—i.e. some 91% is PAF wastes—there is clearly going to be a very large amount of PAF material above ground at the end of mining. Although the current expectation is that the

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waste rock dumps and tailings dams will be covered and rehabilitated as they are (i.e. above ground), this is without doubt unsustainable unless there is acceptance of active management of the site in perpetuity. In other words, the site would need constant monitoring and maintenance to manage AMD risks and ensure protection of the McArthur River itself and the ecosystems and communities that depend on it. From Figure 10, this means that all runoff would need to be tested and managed according to the extent of AMD it contains, including booth surface water runoff and any seepage to groundwater also.

An alternative approach is to relocate all PAF materials to the open cut after mining ceases, and then place NAF material over the top, as shown below in Figure 11. This figure, somewhat optimistically, assumes that the life-of-mine waste balance suggests that there is much greater NAF than PAF wastes—and with the PAF material buried deeper in the pit, this would ensure that these sulfidic wastes are below the re-established groundwater table and therefore minimal oxygen is present to drive AMD generation. Although there may still be risks of impacts on the surrounding groundwater quality, this would, conceptually at the very least, appear to be considerably lower than the Figure 10 scenario of leaving PAF wastes above ground and subject to erosion, infiltration and—in the end—extreme AMD risks for the long-term (probably many decades or longer).

The more realistic scenario, however, is that the PAF materials will be significantly greater in volume than NAF materials that they reach towards the top of the pit and potentially even remain above the re-established groundwater table after mining, as shown in Figure 12. The vast majority of the PAF wastes would be below the water table and present minimal AMD risk, a small quantity would remain above the water table and exposed to fluctuating infiltration and oxygen ingress given the wet–dry tropical climate of the region—leading to some AMD generation, which would seep into the deeper wastes within the pit and create potential to flow downgradient into the surrounding groundwater system. In reality, this is a very complex situation to assess, and given the paucity of data publicly available at present, it remains uncertain as to how realistic this scenario is for the life-of-mine plan for the McArthur River project. There may be technical or engineering options available to address such risks, such as grout curtains around the pit to limit outwards flow, reactive permeable walls made of say finely crushed limestone or other acid-neutralising materials, red mud from bauxite refining, or other approaches often used in contaminated site and AMD remediation projects (there is a wide array of literature on such methods, but this is beyond the scope available for this report).

A recent study of the Tallering Peak iron ore and Nifty copper mines, both in Western Australia, modelled the hydrology and water quality issues of leaving open cuts to form 'pit lakes' versus partial or complete backfilling of waste rock—showing that there can be some risks to groundwater quality from backfilling, and suggesting that pit lakes would therefore be preferable—but it failed to include a model assessing the option of leaving waste rock dumps above ground and the long-term risks to groundwater from AMD generation (see (McCullough *et al*, 2013). Although the Woodcutters site is a positive example of mine rehabilitation which included open cut backfill, there appears to be virtually no reports or papers on the outcomes of this approach, especially with respect to downgradient groundwater systems (the primary concern used to justify backfilling tailings into the former open cut during rehabilitation).

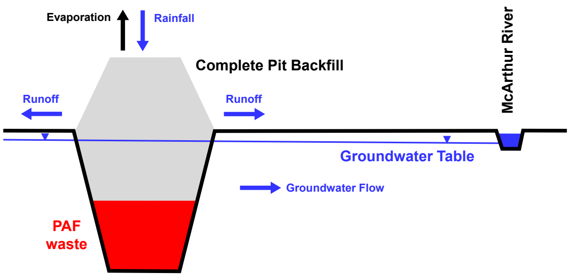

Figure 11: Conceptual representation of the McArthur River site after the end of mining assuming PAF wastes are smaller in volume than NAF wastes and PAF wastes are buried deep in the former open cut

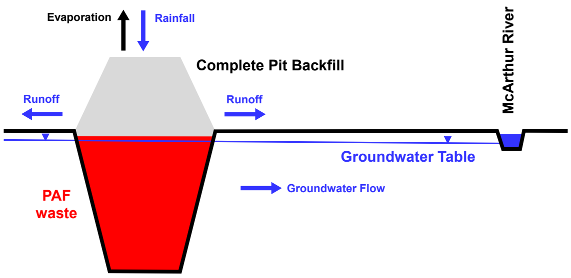

Figure 12: Conceptual representation of the McArthur River site after the end of mining assuming PAF wastes are greater in volume than NAF wastes and PAF wastes are buried deep in the former open cut but still approach the ground surface

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A contrasting example is the former Rum Jungle uranium mine, just south of Darwin, which was a major source of AMD to the Finniss River (this paragraph is summarised from Mudd & Patterson, 2010 and more recently public knowledge of the Rum Jungle site). The mine operated from 1954 to 1971, and no rehabilitation was completed until massive public pressure in the mid-1970's forced the Australian Government to fund works in the mid-1980's at a cost of some $18.6 million (dollars of the day). The total mine wastes at Rum Jungle, including both tailings and waste rock, was about 14 Mt (but excluding the Rum Jungle Creek South mine, since no major AMD issues were present at this site). At the time, residual tailings were excavated from the flood plain and buried in the former open cut and engineered soil covers were used to cover the waste rock dumps and minimise AMD—but within a decade the covers were failing due to ineffective cover design (it allowed the clays to dry out and crack during the dry season, allowing major infiltration in the wet season) and major quality control issues during construction (the covers were not built to the design thickness in some places, further exacerbating the effects of the wet-dry climate and facilitating infiltration). In recent years, AMD has again risen to levels of major environmental concern, and the Australian Government has invested millions of dollars more into new rehabilitation studies—arriving at the need to backfill sulfidic waste rock into the former open cuts, which was rejected in the 1980's due to cost.

Across the Australian and even global mining industry, there are exceedingly few case studies which present detailed assessments of above ground versus backfilling of mine wastes and rehabilitation outcomes—which would almost definitely be related to the lack of regulatory requirements for partial or complete backfill after mining finishes.

At present, it is critical to understand and assess these contrasting end-of-mine scenarios—rehabilitating waste rock dumps and tailings dams above ground (aka Figure 10), or backfilling PAF wastes into the open cut and covering with NAF wastes (aka Figures 11 and 12)—to allow informed decision making on both short and long-term risks, especially AMD generation rates and likely impacts, with the expected costs and benefits of each scenario.

CONCEPTUAL COSTINGS

Given the lack of publicly reported data on current waste volumes at McArthur River, especially the NAF/PAF split, a detailed cost estimate of final rehabilitation including complete pit backfill is impossible. Furthermore, the current financial basis for estimating the size of the rehabilitation bond for the site remains confidential—although the bond was substantially increased in 2015 by the NT Government to reflect the increasing issues with the McArthur River mine. It is possible, however, to develop a coarse estimate of likely costs (based on current costs and not allowing for inflation over time).

The recent rehabilitation scenario study for Rum Jungle (Laurencont *et al*, 2013), although it did not present detailed cost estimates for the preferred strategy of backfilling all sulfidic wastes into the two open cuts, stated that the cost of designing the rehabilitation plan alone was some $11.3 million—quite the contrast to rehabilitation costs in 1986 of $18.6 million (which would be a 2013 value of some $44 million[8]). To understand the contrast with McArthur River, the Rum Jungle site involves the backfill of some 13.3 Mt of waste rock whilst there would be potentially some 700 Mt of waste rock and more than 100 Mt of tailings—suggesting that the design alone for McArthur River would be considerably more.

In open cut mining, the use of large haul trucks requires diesel fuel, and typically this ranges from 0.33 to 1.18 litres per tonne of rock mined (or L/t rock), and averages 0.68 L/t rock (Mudd, 2009a). Other values include 0.98 L/t rock[9] for the (formerly) proposed open cut expansion of Olympic Dam (BHPB, 2009), or 1.17 L/t rock[10] based on a detailed study of the energy and carbon costs of gold mining (Norgate & Haque, 2012). On this data, we could assume a value of say 1 L/t rock, and assuming a conservative value of say $1/L of diesel, this means the ~800 Mt of waste rock and tailings to relocate during rehabilitation would cost of the order of $800 million in diesel alone—but without the costs of trucks, maintenance, labour and related costs. Even if a lower diesel intensity is used, say 0.5 L/t rock, this clearly places the costs of diesel in the ballpark of hundreds of millions of dollars alone.

The final rehabilitation scenario of complete pit backfill would be dominated by the costs of mine waste relocation, with other costs including site personnel, environmental monitoring, other engineering works, water management, and allowance for a contingency to recognise the potential for cost over-runs (as per normal

8 Based on website: www.thomblake.com.au/secondary/hisdata/calculate.php

9 Estimated from 403 million litres (ML) of diesel to mine 410 Mt of rock per year (Tables 5.1, 5.2).

10 Based on 5.3 kg of diesel per tonne of ore mined (i.e. 5.3 kg/t ore), 3 tonnes of waste rock per tonne of ore and a density of diesel of 1.135 L/kg (from (OCE, 2016).

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engineering and financial practice). As highlighted by the Woodcutters site, rehabilitation often turns out to be much more expensive than initial expectations—but comprehensive studies documenting the true costs of rehabilitation across the modern mining industry (i.e. mines operated and rehabilitated since the 1980's) are completely lacking, especially comparing rehabilitation bonds held by government versus final actual costs. For McArthur River, there remains no public confirmation of the expected rehabilitation costs (which at present is above ground waste rock dumps and the tailings dam) versus the bond held by the NT Government, including the technical and financial basis for this—despite the bond being increased in 2015 after considerable pressure by the NT Government.

LONG-TERM MINING IN THE REGION

As noted previously, the McArthur River project currently reports a mineral resource of some 178.3 Mt—although the 2012 EIS allowed for the mining of some 117.5 Mt (as of 2012, minus production 2013 to 2015 of some 9.3 Mt)—suggesting that there is still an additional ~60 Mt possible to mine, or another 10–12 years worth. In addition, the recent announcement of the Teena Pb–Zn–Ag discovery, some 8 km west of the McArthur River site, shows a mineral resource of 58 Mt at similar grades. Overall, this means that there is an even greater long-term scale of mining possible for the McArthur River project and region than envisaged by current EIA approvals. Future assessments need to consider such possible scenarios in conjunction with current operations and plans, as the cumulative environmental (and social) risks grow as project scales expand.

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SUMMARY AND KEY RECOMMENDATIONS

The history of the McArthur River Pb–Zn–Ag project is one of under-estimating long-term environmental risks, with the poor prediction of the severity of acidic drainage from sulfidic mine wastes being the most fundamental failure to date. Despite three periods of detailed environmental impact assessment (1992, 2005–06, 2012), the problems at McArthur River have continued to escalate, dominated by acidic drainage issues—raising legitimate questions concerning the efficacy of current NT EIA processes to understand and assess risks presented by projects such as McArthur River. In order to improve public understanding and transparency around the variety of complex issues at the site, the following recommendations are made:

- Full details of waste rock mined, tailings produced and their composition (i.e. PAF versus NAF) should be reported annually, and these reports and datasets made publicly available—an account should also be provided on all mining to date, with future reports always including all historical data over time;
- Continuous water quality monitoring, such as pH, electrical conductivity (EC) and possibly sulfate (SO_4), should be implemented across the site, especially at key seepage or drainage sites from the waste rock dumps and tailings dam cells as well as upstream and downstream in the McArthur River and Barney and Surprise Creeks;
- All environmental monitoring data, held by both the McArthur River site and the NT Government, should be made publicly available, and as above, continue to be made available into the future;
- Full details concerning the current rehabilitation bond held by the NT Government (through the NTDME), including the technical and financial basis, with a particular focus on current criteria for rehabilitation and the life-of-mine plan;
- Similarly to the Ranger uranium mine, annual plans of rehabilitation should be prepared and part of regulatory requirements—but unlike Ranger, they should be made public to ensure transparency about the current rehabilitation bond, expected mining plans and the capacity to fund and achieve an acceptable rehabilitation outcome for the site;

To ensure that all issues are assessed and understood in a comprehensive manner, it is clear that current NT EIA processes are ineffective at addressing such complex sites as McArthur River—meaning a higher level of assessment is required. At present, the NT EIA process does not allow for a public inquiry level of assessment—only an EIS or PER are possible, compared to the normal EIA processes which allow for a PER, EIS or full public inquiry level of assessment, whereby a public inquiry is akin to the processes of a Royal Commission. Furthermore, the current guidelines for the 'Overburden Management EIS' (NTEPA, 2014) do not explicitly require the scenario of complete pit backfill to be included in the EIS (which is currently expected to be publicly released in late 2016), simply requesting the following information (p. 12):

- *Outline rehabilitation, including progressive rehabilitation, revegetation and closure plans on site in consideration of the changed management requirements for waste rock since the previously authorised Phase 3 project;*
- *Describe proposed post-mining land uses which have been identified and agreed on through consultation with stakeholders; and*
- *Detail the availability, sources and volumes of suitable materials required for rehabilitation, revegetation and mine closure (e.g. clay, capping materials).*

Furthermore, the risk assessments required imply that only above ground management needs to be considered and assessed, as the focus is *"… on the final pit lake water quality"* and *"… integrity of management structures"* as well as no explicit reference in the requirements for a conceptual mine closure plan to consider the scenario of complete pit backfill (p. 13).

As such, there is a clear and legitimate case for an expanded assessment scope of the future of the McArthur River project—and given the failures of the NT EIA process to date, a higher-level public inquiry is required. Although this is not allowed for in current NT EIA processes (unlike its state and federal counterparts), an effective option would therefore be a public commission of inquiry held under the NT Inquiries Act (2011). This would need to include not only the NT Government but also the Commonwealth Government, given the need to consider matters of national environmental significance under federal EIA legislation (namely the *Environment Protection & Biodiversity Conservation Act 1999*, or EPBC Act). The primary focus should be on the current status of the McArthur River site, especially a detailed audit of current mine wastes and management strategies (including an assessment of PAF and NAF wastes), future mine plans and ultimately whether the project can be operated in a manner which achieves acceptable environmental outcomes both during operations and after rehabilitation.

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A key area of investigation of such an inquiry should be the various options for final site rehabilitation, their expected environmental outcomes and the relative costs of each rehabilitation scenario. Whether mining should stop in the meantime is an important area of public debate—clearly there are many complex questions involved in the short and long-term management of the McArthur River project, with significant implications for the future of the ecosystems and communities of the region. As such, the final recommendation from this study is simply:

- Initiate and conduct a public inquiry under the NT Inquiries Act (2011) to investigate the current status and future plans of the McArthur River project, including a detailed assessment of rehabilitation scenarios which look at complete pit backfill and current regulatory requirements, especially the adequacy of the rehabilitation bond and related financial aspects—the primary issue is whether the McArthur River project can be operated and rehabilitated safely in a manner which meets legitimate community expectations for a modern mining project.

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REFERENCES

Agricola, G, 1556, *De Re Metallica*. 1950 Reprint, H C Hoover and L H Hoover (Ed's), Dover Publications, New York, USA.

BHPB, 2009, *Olympic Dam Expansion—Draft Environmental Impact Statement*. BHP Billiton Ltd (BHPB), Adelaide, SA, May 2009.

Blowes, D W, Ptacek, C J, Jambor, J L & Weisener, C G, 2003, *The Geochemistry of Acid Mine Drainage*. In "Treatise on Geochemistry", H D Holland & K K Turekian (Ed's), Vol. 9 of 9, Chap. 9.05, pp 149–204.

Blowes, D W, Ptacek, C J, Jambor, J L, Weisener, C G, Paktunc, D, Gould, W D & Johnson, D B, 2014, *The Geochemistry of Acid Mine Drainage*. In "Treatise on Geochemistry 2nd Edition", H D Holland & K K Turekian (Ed's), Vol. 11 of 11, Chap. 11.5, pp 131–190.

CCNT, 1992, *McArthur River Project—Proposed Zinc–Lead–Silver Mine: Environmental Assessment Report and Recommendations*. Environment Protection Unit, Conservation Commission of the Nothern Territory (CCNT), Darwin, NT, August 1992, 85 p.

Dold, B, 2014, *Evolution of Acid Mine Drainage Formation in Sulphidic Mine Tailings*. Minerals, 4: pp 621–641.

Dowd, P, 2005, *The Business Case for Prevention of Acid Drainage*. Proc. "The International Network for Acid Prevention (INAP) Conference", 23 August 2005, 10 p.

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 Document no. 2000/016, European Environmental Bureau (EEB), October 2000, 32 p.

EES, 2009, *Independent Monitor Audit of the Environmental Performance of the McArthur River Mine—2008 Operational Period*. Prepared by Environmental Earth Sciences Pty Ltd (EES) for the NT Dept. of Regional Development, Primary Industry, Fisheries & Resources, Melbourne, VIC, August 2009, 171 p.

EES, 2010, *Independent Monitor Audit Report—Environmental Performance of the McArthur River Mine—2009 Operational Period*. Prepared by Environmental Earth Sciences Pty Ltd (EES) for the NT Dept. of Resources, Melbourne, VIC, August 2010, 201 p.

EES, 2011, *Independent Monitor's Audit of the McArthur River Mine for the 2010 Operational Period*. Prepared by Environmental Earth Sciences Pty Ltd (EES) for the NT Minister for Primary Industry Fisheries & Resources, Melbourne, VIC, October 2011, 256 p.

EES, 2012, *Independent Monitor Audit of the McArthur River Mine for the 2011 Operational Period*. Prepared by Environmental Earth Sciences Pty Ltd (EES) for the NT Minister for Mines & Energy, Melbourne, VIC, October 2011, 258 p.

ERIAS, 2014, *Independent Monitor—Environmental Performance Annual Report 2012–2013—McArthur River Mine*. Prepared by ERIAS Group Pty Ltd (ERIAS) for the NT Minister of Mines & Energy and the NT Dept. of Mines & Energy, Melbourne, VIC, October 2014, 462 p.

ERIAS, 2015, *Independent Monitor—Environmental Performance Annual Report 2014—McArthur River Mine*. Prepared by ERIAS Group Pty Ltd (ERIAS) for the NT Minister of Mines & Energy and the NT Dept. of Mines & Energy, Melbourne, VIC, October 2014, 674 p.

Ferguson, B & Mudd, G M, 2011, *Water Quality, Water Management and the Ranger Uranium Project: Guidelines, Trends and Issues*. Water Air and Soil Pollution, 217(1): pp 347–363.

Fountain, C, 2002, *Isasmelt and IsaMills—Models of Successful R&D*. Proc. "Young Leaders Conference", Australasian Institute of Mining & Metallurgy (AusIMM), Kalgoorlie, WA, 19–21 March 2002, 12 p.

Franks, D M, 2015, *Mountain Movers: Mining, Sustainability and the Agents of Change*. Routledge, 194 p.

GE, 2016, *Google Earth*. Google Earth (GE), Google Inc, Accessed 9 August 2016, earth.google.com.

Glencore, var.-a, *Annual Report*. Glencore Plc, Zug, Switzerland, Years 2013 to 2015.

Glencore, var.-b, *Glencore Reserves & Resources as at December*. Glencore Plc, Zug, Switzerland, Years 2013 to 2015.

Glencore, var.-c, *Production Reports for the 12 Months Ended December*. Glencore Plc, Zug, Switzerland, Years 2013 to 2015.

Howey, K, 2010, *The Northern Territory and the McArthur River Mine*. In "Mills, Mines and Other Controversies—The Environmental Assessment of Major Projects", T Bonyhady & A Macintosh (Ed's), The Federation Press, Leichhardt, NSW, pp 60–80.

INAP, 2010, *Global Acid Rock Drainage Guide*. Rev. 1, www.gardguide.com, International Network for Acid Prevention (INAP), December 2010.

Johnston, J & Murray, G (Ed's), 1997, *Managing Sulphidic Mine Wastes and Acid Drainage*, Best Practice Environmental Management in Mining Series, Environment Australia, Canberra, ACT.

Kempton, H, Bloomfield, T A, Hanson, J L & Limerick, P, 2010, *Policy Guidance for Identifying and Effectively Managing Perpetual Environmental Impacts From New Hard Rock Mines*. Environmental Science and Policy, 13(6): pp 558–566.

Laurencont, T, Dixon, I, Edwards, C, Fawcett, M, Ferguson, P, Keliher, L, Kraatz, M, Leitch, V, Lewis, B, Markham, A, Rider, M, Smith, H, Smith, R, Unger, C, Waggitt, P & Walton, R, 2013, *Former Rum Jungle Mine Site—Conceptual Rehabilitation Plan, May 2013*. NT Department of Mines & Energy (NTDME), Darwin, NT, 31 July 2013, 130 p.

Logan, R G, Murray, W J & Williams, N, 1990, *HYC Silver–Lead–Zinc Deposit, McArthur River*. In "Geology of the Mineral Deposits of Australia and Papua New Guinea—Vol 1", F E Hughes (Ed.), Australasian Institute of Mining & Metallurgy (AusIMM), Melbourne, VIC, Monograph 14, pp 907–911.

Lottermoser, B, 2010, *Mine Wastes—Characterisation, Treatment, Environmental Impacts*. 3rd Edition, Springer-Verlag, Berlin, Germany, 400 p.

McCullough, C D, Marchand, G & Unseld, J, 2013, *Mine Closure of Pit Lakes as Terminal Sinks: Best Available Practice When Options are Limited?* Mine Water and the Environment, 32: pp 302–313.

MIM, var.-a, *Annual Report*. Mt Isa Mines Ltd (MIM), Brisbane, QLD, Years 1990 to 2002.

MIM, var.-b, *Quarterly Report*. Mt Isa Mines Ltd (MIM), Brisbane, QLD, Years September 1994 to March 2003.

CONTINUED »

Mudd, G M, 2007, *An Analysis of Historic Production Trends in Australian Base Metal Mining*. Ore Geology Reviews, 32(1–2): pp 227–261.

Mudd, G M, 2008, *Environmental Regulation of Uranium Mining on Indigenous Land Surrounded by a World Heritage-Listed National Park: A Brief Review of the Ranger Uranium Project*. National Environmental Law Review, 1: pp 36–42.

Mudd, G M, 2009a, *Prediction of Greenhouse Gas Emissions for the Olympic Dam Mega-Expansion. Environmental Engineering*, Dept. of Civil Eng. Monash University, Clayton, VIC, April 2009, 13 p.

Mudd, G M, 2009b, *The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future*. Department of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne, VIC, October 2007; Revised April 2009, 277 p, users.monash.edu.au/~gmudd/sustymining.html.

Mudd, G M & Boger, D V, 2013, *The Ever Growing Case for Paste and Thickened Tailings—Towards More Sustainable Mine Waste Management*. AusIMM Bulletin, April 2013(2): pp 56–59.

Mudd, G M, Jowitt, S M & Werner, T T, 2016, *The World's Lead–Zinc Mineral Resources: Scarcity, Data, Issues and Opportunities*. Ore Geology Reviews, In Press.

Mudd, G M & Patterson, J, 2010, *Continuing Pollution From the Rum Jungle U–Cu Project: A Critical Evaluation of Environmental Monitoring and Rehabilitation*. Environmental Pollution, 158(5): pp 1252–1260.

Newcrest, 2012, *Cadia Valley Operations Annual Environmental Management Report (July 2010–June 2011)*. Newcrest Mining Ltd, Melbourne, VIC, February 2012, 952 p.

Nordstrom, D K & Alpers, C N, 1999, *Geochemistry of Acid Mine Waters. The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques and Health Issues. G S Plumlee & M J Logsdon. Society of Economic Geologists (SEG)*, Reviews in Economic Geology, Vol. 6A: pp 133–160.

Norgate, T E & Haque, N, 2012, *Using Life Cycle Assessment to Evaluate Some Environmental Impacts of Gold Production*. Journal of Cleaner Production, 29–30: pp 53–63.

NTEPA, 2014, *Terms of Reference for the Preparation of an Environmental IMpact Statement—McArthur River Overburden Management Project*. NT Environmental Protection Authority (NTEPA), Darwin, NT, September 2014, 24 p.

OCE, 2016, *Energy in Australia 2015*. Prepared by the Office of the Chief Economist (OCE) for the Dept. of Industry, Innovation & Science, Canberra, ACT, January 2016, 138 p.

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

Porterfield, D C, Miller, S & Waters, P, 2003, *A Strategy for Managing Acid Rock Drainage in Arid Climates—The Mt Whaleback Story*. Proc. "6TH ICARD: International Conference on Acid Rock Drainage", T Farrell & G Taylor (Ed's), Australasian Institute of Mining & Metallurgy (AusIMM), Cairns, QLD, July 2003, pp 143–146.

Roberts, T, 2005, *Frontier Justice: A History of the Gulf Country to 1900*. University of Queensland Press, St Lucia, QLD, 316 p.

Rossberg, F & Pafumi, J, 2013, *McArthur River Mine*. In "Australasian Mining and Metallurgical Operating Practices—The Sir Maurice Mawby Memorial Volume: Third Edition", W J Rankin (Ed.), Australasian Institute of Mining & Metallurgy (AusIMM), Melbourne, Australia, Monograph 28, pp 1661–1682.

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

Stewart, C M & Gwynne, M, 1998, *An Overview of Current Planning and Production Systems at McArthur River Mine*. Proc. "Underground Operaters Conference", Australasian Institute of Mining & Metallurgy (AusIMM), Townsville, QLD, 30 June—3 July 1998, pp 95–101.

Taylor, J & Pape, S (Ed's), 2007, *Managing Acid and Metalliferous Drainage. Leading Practice Sustainable Development Program for the Mining Industry*, Commonwealth Department of Industry, Tourism and Resources, February 2007, Canberra, ACT, 107 p.

URS, 2005, *McArthur River Mine Open Cut Project—Draft Environmental Impact Statement*. Prepared by URS Pty Ltd for McArthur River Mining Pty Ltd and Xstrata Ltd, Darwin, NT, August 2005.

URS, 2006, *McArthur River Mine Open Cut Project—Public Environment Report*. Prepared by URS Pty Ltd for McArthur River Mining Pty Ltd and Xstrata Ltd, Darwin, NT, July 2006.

URS, 2012, *McArthur River Mine Phase 3 Development Project—Draft Environmental Impact Statement*. Prepared by URS Pty Ltd for McArthur River Mining Pty Ltd and Xstrata Ltd, Darwin, NT, February 2012.

Verburg, R, 2011, *Mitigating Acid Rock Drainage*. In "SME Mining Engineering Handbook (3rd Edition)", P Darling (Ed.), Society for Mining, Metallurgy, and Exploration (SME), Denver, USA, pp 1721–1731.

Warner, N A, 1998, *Refined Zinc Metal Production at the Minesite*. Proc. "AusIMM Annual Conference 1993—The Mining Cycle", Australasian Institute of Mining & Metallurgy (AusIMM), Mount Isa, QLD, 19–23 April 1998, pp 417–425.

Xstrata, var.-a, *Annual Report*. Xstrata Plc, Zug, Switzerland, Years 2002 to 2011.

Xstrata, var.-b, *Ore Reserves and Mineral Resources*. Xstrata Plc, Zug, Switzerland, Years 2006 to 2012.

Xstrata, var.-c, *Production Reports for the 12 Months Ended December*. Xstrata Plc, Zug, Switzerland, Years 2006 to 2012.

Xstrata, var.-d, *Sustainability Report—McArthur River Mining*. Xstrata Plc, Zug, Switzerland, Years 2005 to 2008.

Xstrata, var.-e, *Sustainability Report—Xstrata Zinc Australia*. Xstrata Plc, Zug, Switzerland, Years 2009 to 2011.

Young, A, 2015, *McArthur River Mine: The Making of an Environmental Catastrophe*. Australian Environmental Law Digest, January 2015, 2(1): pp 15–22.

CONTINUED »

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