

SUCCESSFULLY LOWERING THE RISKS AND COSTS ASSOCIATED WITH THE LEGACY OF THE ABANDONED BRUKUNGA PYRITE MINE, SOUTH AUSTRALIA¹.

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Abstract. Pyrite (FeS₂) and pyrrhotite (FeS) were mined by open pit methods at Brukunga, South Australia, between 1955 and 1972. Eight million tonnes of waste rock (2 wt.% S) and 3.5 Mt of tailings (1.7 wt.% S) were produced. Oxidation of this material, and remaining in-situ rock mass, has resulted in acid drainage (pH<3) with elevated sulphate and dissolved metals. Prior to June 2003 this acid drainage entered Dawesley Creek making the water unsuitable for livestock and irrigation use for up to 20 km downstream. The site is now under the care of the State Government.

A lime neutralization plant commissioned by the State Government in 1980 and currently operated by Primary Industries and Resources South Australia (PIRSA), a government body, was built to address water quality issues on site and reduce downstream impacts in Dawesley Creek. Construction of a drain in June 2003 diverted flow from Dawesley Creek around the mine enabling all acid drainage to be retained, collected and treated on site. Upgrade of the existing plant to High Density Sludge (HDS) mode resulted in additional improvements in water quality, increased reagent efficiency and reduced overall treatment costs, including a 50% cost savings on sludge handling and disposal. An additional plant has been commissioned to cope with increased treatment volumes brought about by improvements in the containment and collection of acid drainage from the site.

Having substantially reduced the water quality risks to downstream users PIRSA's ongoing rehabilitation of the site is aimed at lowering the acid load entering the treatment plants. Future stages in the rehabilitation program include plans to move and cap waste rock piles and to continue to revegetate the site. This will further reduce treatment and sludge handling costs while maintaining water quality for users downstream of the site.

Additional Key Words: minesite rehabilitation, acid and metalliferous drainage (AMD), High Density Sludge (HDS), lime treatment plant

¹ Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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7th International Conference on Acid Rock Drainage, 2006 pp 365-377

DOI: 10.21000/JASMR06020365

<http://dx.doi.org/10.21000/JASMR06020365>

Introduction

The Brukunga pyrite mine is located 4 km north of Nairne and 40 km east of Adelaide in the Mount Lofty Ranges of South Australia (Fig. 1). Iron sulfide (pyrite and pyrrhotite) was mined at the site between 1955 and 1972. During mining operations, two large waste rock piles were generated from approximately 8 million tonnes of sulfidic overburden material (2 wt.% S), and a valley-fill tailings facility adjacent to the mine was filled with 3.5 million tonnes of sulfidic sand-tailings (1.7 wt.% S) (PIRSA, 2003a).

Acid and Metalliferous Drainage (AMD) has been a significant issue at the Brukunga mine as a result of the oxidation of pyrite and pyrrhotite minerals within the waste rock piles, tailings facility and the unsaturated zone of the in-situ rock mass. This process continues to generate acidic water at the site, with pHs of 2.5-2.9 and highly elevated SO_4^{-2} and metal concentrations recorded between September 1999 and December 2003.

Until June 2003, acid drainage entered Dawesley Creek, which flowed directly through the Brukunga mine site. Elevated levels of SO_4^{-2} and metals (eg. Al, Fe, Cd, and Mn) were carried downstream into Mt. Barker Creek, Bremer River and finally into Lake Alexandrina, making the water unsuitable for livestock and irrigation use up to 20 km downstream of the mine site. PIRSA are working to reduce risks and lower treatment costs associated with the abandoned mine.

Site History

The 'historic' Brukunga mine has not been worked since the mine closed 31 May 1972. The mine was established in the 1950's as a source of S to be converted to H_2SO_4 for use in the manufacture of superphosphate fertilizer. At the time superphosphate fertilizer was in demand due to the poor quality of Australian soils and the expansion of post-war agricultural activities.

The development of the mine was encouraged and sponsored by both the State and Commonwealth Governments as part of the drive for self-sufficiency and full employment. The State Government fostered the formation of the company, Nairne Pyrites Pty Ltd, a consortium of three fertilizer manufacturers and a mine operator; ie. Cresco Fertilisers; Adelaide Chemical Co; Wallaroo-Mt Lyell Fertilisers; and The BHP Company.

The mine commenced production in June 1955 and continued for 17 years, closing on the 31st May 1972. The mine produced 5.5 million tonnes of Fe sulfide (pyrite and pyrrhotite) ore at ~380,000 tonnes per annum. The ore had a grade of 11% S and was crushed and processed on site to produce a 40% S concentrate.

Iron sulfide was quarried from the side of two steep hills using a power shovel and trucks. The mine concentrate was trucked to a rail siding at Nairne and then railed to Snowdens Beach, Port Adelaide where it was converted to H_2SO_4 . Imported phosphate rock was treated with the acid to produce superphosphate fertilizer to sustain South Australian agriculture.

To encourage mining of pyrite for production of sulphuric acid, the Commonwealth paid a bounty via the Sulphuric Acid Bounty Act, 1954 and the Pyrites Bounty Act, 1960. Only two mines were established in Australia specifically to mine pyrite ore, ie. Brukunga and the King Mine at Norseman, Western Australia. In the late 1960's cheaper sources of sulfur became available mainly due to Canada's refining of 'sour natural gas'. The government withdrew the

pyrite subsidy on 31st May 1972 and both pyrite mines ceased mining operations on the same day.

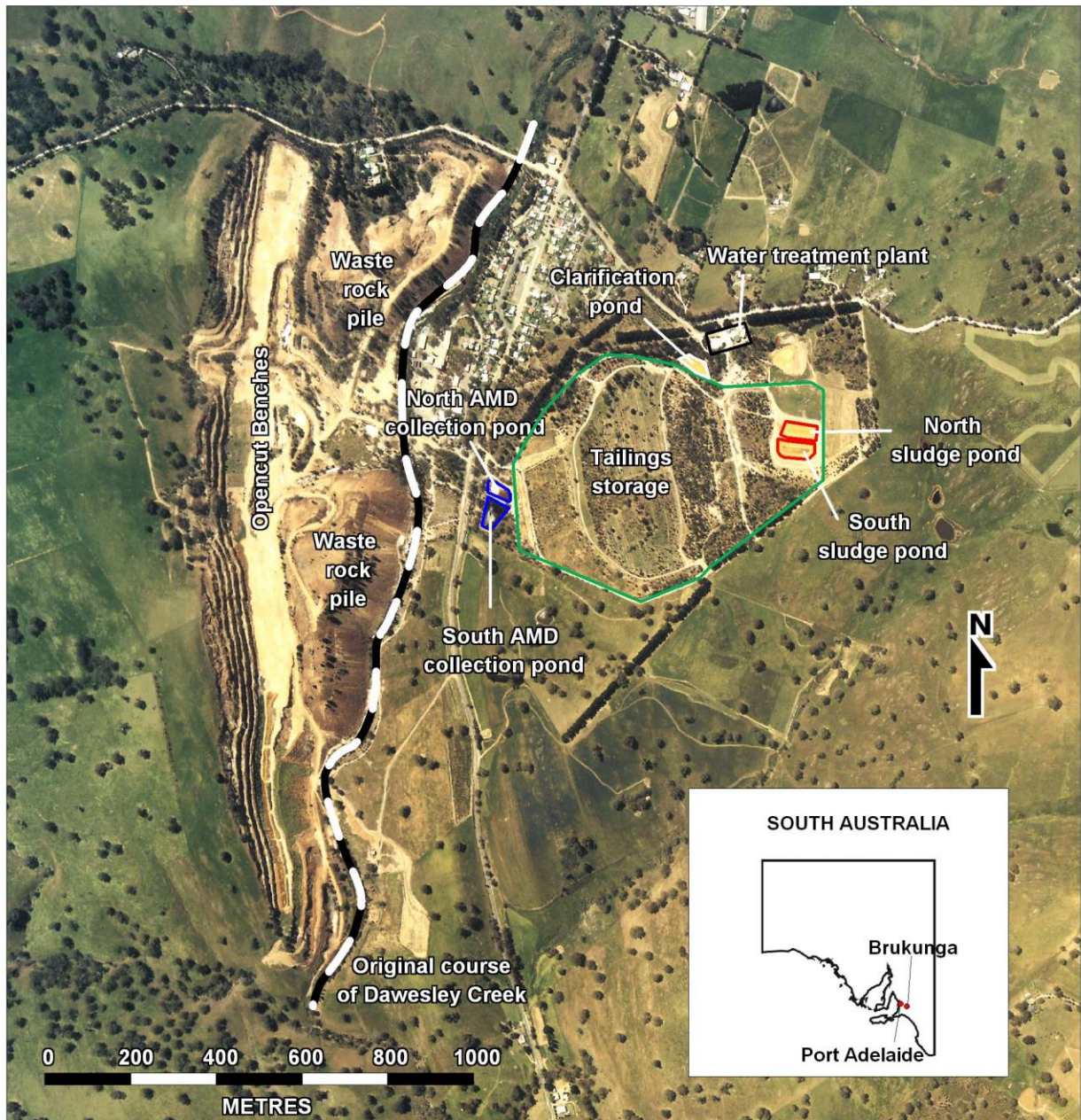


Figure 1. Location of the Brukunga Pyrite Mine and key site features.

Following mine closure, the crushers and metallurgical plant were dismantled and the mine office and workshops later became the start of the Country Fire Service (CFS) State Training Headquarters. The remaining quarry bench is 1.8 km long with 2 high walls 70 and 85 m laid back at 45° and 50°. The 8 Mt of rock removed to access the pyrite was discarded to form the north and south waste rock piles. A small rock pile, south-east of the open cut, has been rehabilitated.

Concentration of the sulfide ore on site involved crushing and grinding the ore to a fine sand, with 80% passing a 75 µm sieve. This produced a total of 3.5 Mt of mill tailings that was pumped to the eastern side of Nairne Road to fill a shallow farm valley. The tailings at the front edge are 30 metres above the valley floor and covers an area of 28 hectares.

After closure in 1972, Nairne Pyrites Pty Ltd employed two caretakers to collect and pump acid drainage to a large evaporation lake on the tailings facility. In February 1974, a summer storm caused the lake to overflow and it was soon realised that water levels could not be controlled solely by evaporation. The Department of Mines and Australian Mineral Development Laboratories (AMDEL) began to investigate site water quality issues. In August 1977, the State Government accepted responsibility for rehabilitation of the site.

In September 1980, the government commissioned a lime treatment plant to treat the acid water. The Department of Engineering and Water Supply (EWS) were appointed the operators and within 5 years of successful treatment a 10 ha lake of acid water was removed from the tailings facility. The plant was then used to treat acidic seepage percolating through the tailings embankment and acid drainage transferred by 12 float-activated pumps from various locations around the quarry bench and waste rock piles. The collected water is held in two ponds located at the base of the tailings embankment. Polluted water from the holding ponds is pumped to the plant by a range of six varying capacity screw-pumps mounted in parallel. Feed to the plant (from 17 kL/hour to a peak of 50+ kL/hour) is controlled by operating one or more of these pumps.

Prior to 2003, where possible, contaminated water from Dawesley Creek was diverted, via the collection ponds, through the lime treatment plant before being discharged back into the creek. However, the capacity of the treatment plant was frequently exceeded due to high flows in Dawesley Creek, especially during the wetter winter months.

Despite all the work done from 1980 to 2003 to intercept and treat acid drainage, only approximately half the pollution from the site was treated. The remnant 50% or ~600 tonnes/year of SO_4^{-2} escaped to pollute the flow in Dawesley Creek (PIRSA, 2003b).

Site Issues

The main environmental risk at Brukunga is caused by the natural oxidation of pyrite and pyrrhotite minerals within the waste rock piles, tailings facility and unsaturated zone of the in-situ rock mass, producing acid drainage that may enter Dawesley Creek.

In 1993-94 the Australian Nuclear Scientific and Technology Organisation (ANSTO) were engaged to provide an estimate of how long the oxidation would continue. Temperature and oxygen concentrations were monitored in a series of boreholes drilled into the tailings and rock piles, and results indicated that acid-forming reactions are likely to continue for between 240 and 750 years (ANSTO, 1994).

In March 1999, the Brukunga Mine Site Remediation Board (BMSRB) replaced the technically based 'Brukunga Taskforce' placing emphasis on local community involvement in developing new management solutions to lower the risks associated with the acid drainage. The BMSRB advises the State Government Minister for Primary Industries and Resources on strategies for environmental improvement and has representatives from the Dawesley Creek

Catchment Landcare Group, the District Council of Mount Barker, a local community representative, and members from PIRSA (Minerals and Energy Division).

In 2001, after considering various studies, the BMSRB recommended a \$26M (AUD) 10 year program of new initiatives to the Minister and government (PIRSA, 2002). The government accepted the program involving: 1) creek diversion and containment of site acid drainage, 2) doubling the peak acid treatment capacity and 3) decreasing the acid seepage by relocating / capping waste rock piles.

Containment of site acid drainage

As a priority of the remediation program, acid drainage produced on site had to be contained and the amounts entering the local waterways substantially reduced. The key to this was the diversion of Dawesley Creek, and containment of acid runoff and seepage on site.

In June 2003, Stage 1 of the program, construction of the Dawesley Creek diversion, was successfully completed. The diversion isolates Dawesley Creek from the pollution generated at the mine site. The 1.7 km diversion includes 780 metres of 1.5 metre diameter reinforced concrete pipes, 175 metres of High-Density Polyethylene (HDPE) plastic pipe and 750 metres of drilled and blasted open channel (Fig. 2). The original section of creek, adjacent to the waste rock piles, now provides a sink for the collection of acid drainage that previously flowed directly into the creek. Construction of the drain resulted in an immediate improvement in water quality in Dawesley Creek downstream of the mine for the first time in 50 years.



Figure 2. Dawesley Creek diversion drain. Laying pipe for the underground segments of the drain (right) and open channels (left).

On completion of the Dawesley Creek diversion it became possible to intercept 90-95% of the pollution, with most of the loss occurring during high rainfall events. During these high rainfall events, any loss of acid drainage off site was substantially diluted.

Slaked-lime Treatment Plant

The vast improvements in the capture and containment of acid drainage on site brought about by the Dawesley Creek diversion required the upgrade of treatment facilities to cope with the increased treatment requirements. Stage 2 of the remediation program required the doubling of the peak acid treatment capacity of the site. This was achieved by upgrading the existing plant and commissioning of a new plant.

Existing Plant

The existing treatment plant was designed to treat 20 kL of acid drainage per hour, but has dealt with flow rates between 10 and 35 kL per hour. Treatment requirements are greatly affected by seasonal and local rainfall events. During summer the plant is often shut down, but during the wet winter months (June through September) the plant operates 24 hours/day and 7 days/week to maintain water levels in the North and South AMD holding ponds.

Untreated water typically has low pH (2.5-2.9), high conductivity (6,970-11,800 $\mu\text{S}/\text{cm}$), high concentrations of SO_4^{-2} (8,240-14,000 mg/L) and elevated Al, Cd, Cr, Cu, Fe, Pb, Mn, Ni and Zn. This water is pumped from the North AMD holding pond (Fig. 3) into the first of three 12 kL reactor tanks (Reactor 1) in the treatment plant (Fig. 4).

Carbide lime slurry is mixed in a 50 kL below ground tank (Fig. 5), and dispensed to Reactor 1 as required to achieve a pH of approximately 9.5 in water exiting the plant. The carbide lime is a form of hydrated lime that is a by-product of the acetylene manufacturing process. The reagent therefore contains minor impurities (eg. CaC_2) that is not present in conventional hydrated lime. Carbide lime slurry is delivered to the site by road tanker 3 days a week. Excess slurry is stored in an evaporation pond to the west of the plant. Partially-dried carbide lime from the evaporation pond is transferred to one of two above-ground temporary storage areas. When required, the partially-dried carbide lime is added (with water) to the 50 kL below ground lime slurry tank. Annual consumption of reagent is variable but averages approximately 600 dry tonnes per annum.



Figure 3. Acid drainage from the site is pumped to the North AMD holding pond (shown) prior to treatment.



Figure 4. Reactors 1, 2 and 3 as viewed from the thickener tank (existing plant).

Water from Reactor 1 flows by gravity to Reactor 2 and (subsequently) to Reactor 3. The use of three reactor vessels provides the retention time required for the completion of the treatment reactions. Water exiting Reactor 3 then flows into a below ground sump. When the sump is full, water is pumped up to a 390 kL thickener / clarifier tank. Flocculent is dispensed into the stream of water from the below ground sump before it enters the thickener / clarifier tank (Fig. 6). Clear supernatant water from the thickener / clarifier tank overflows to a clarification pond before being released into Dawesley Creek, downstream of the mine site.



Figure 5. Below ground hydrated lime storage, mixing and dosing system.



Figure 6. Thickener / clarifier tank.

Settled sludge in the base of the thickener / clarifier tank is either recycled into Reactor 2 or pumped to one of two sludge ponds located on the tailings facility. The low-density sludge exiting the plant prior to its upgrade was between 3 and 5 wt% solids.

Prior to its upgrade the existing plant treated 54,258 kL and 123,098 kL of low pH water in 2002 and 2003 respectively. This treatment required 484 and 723 dry tonnes of carbide lime respectively. Increased treatment volumes in 2003 corresponded to the higher rainfall and the diversion of Dawesley Creek in June 2003, which enabled virtually all AMD from the site to be collected for treatment. The pH of water exiting the thickener / clarifier tank in 2003 ranged from 7.5 to 11.0 (average 9.2). The pH decreased significantly in the clarification pond (minimum 6.5, average 8.6, maximum 10.2) and further decreased prior to being released to Dawesley Creek (minimum 6.0, average 7.5, maximum 9.3). The low-density sludge produced contained approximately 4.4 wt% solids.

Operating in Low Density Sludge (LDS) mode the pH increased from 2.7 to around 7.4-8.4 after addition of lime to the AMD in Reactor 1. Electrical Conductivity (EC) decreased from 10,300-10,410 $\mu\text{S}/\text{cm}$ to 4,180-5260 $\mu\text{S}/\text{cm}$, and the water had become highly reduced, with oxidation-reduction potential (ORP) values as low as -246 mV. Variation in pH, EC and ORP with depth in Reactor 1 indicated that mixing was inefficient.

As water flowed from Reactor 1 to 3 the pH generally decreased (eg. 10.9-9.3) along with the EC (eg. 4,300-3,933 $\mu\text{S}/\text{cm}$), and the water became less reduced (eg. ORP increased from -148 to -80 mV).

Thickener / clarifier tank overflow water was characterised by relatively high pH (8.9-10.0), lower EC (3,833-3,857 $\mu\text{S}/\text{cm}$) and still relatively reduced water (eg. ORP values -78 to +21 mV).

Water in the clarification pond had significantly lower pH (6.5-8.0) and higher EC (4,348-4,460 $\mu\text{S}/\text{cm}$), indicating the presence of mineral acidity in the thickener / clarifier tank overflow water.

Tests carried out by Earth Systems (2004) indicated that metal removal efficiencies of at least 98 wt.% are likely to have been routinely achieved in the existing plant when it was operating in Low Density Sludge (LDS) mode. Low concentrations of redox sensitive soluble components (Fe and Mn) accounted for the residual 2 wt.%. As a result of this low soluble metal content, treated water was being discharged from the plant with low level acidity values (10-100 mg/L CaCO_3). Approximately 1.5 to 2 log unit falls in pH were being recorded between the plant overflow and the Dawesley Creek discharge as a result of ongoing oxidation and related acidification of the treated water.

Upgrade of existing plant

The identification of several inefficiencies in the existing plant was detailed in a report commissioned for Stage 2 of the site remediation works (Earth Systems, 2004). Key inefficiencies included: 1) the incomplete oxidation of AMD during the treatment process, which allowed water to be discharged with residual mineral acidity, and 2) large volumes of low density sludge that presented storage and handling problems.

To address the low levels of redox sensitive soluble metals being discharged from the plant, modifications were made to fully oxidize the treated water stream. Tests were conducted on the plant operating in LDS mode with oxygen supplied via a compressor. This resulted in very low to below detection metal concentrations and high residual alkalinities (1,300-3,600 mg/L CaCO_3 equivalent) in the discharge stream. As a result a high capacity air blower (115-130 m^3/hour) was added to the existing plant (Reactor 2 and 3).

Issues associated with sludge production and storage were addressed by converting the plant to High Density Sludge (HDS) mode. Conversion to HDS mode was achieved by pre-treating the raw acid water feed in Reactor 1 with high volumes of alkaline sludge from the thickener / clarifier tank. This raises the pH to 6.5 before new lime slurry is added in Reactor 2. Recycling of sludge within the treatment plant has improved reagent efficiencies and reduced sludge volumes by increasing the sludge density. An advanced polymer flocculant AN905MPM is added to the thickener tank to assist settling and further increase sludge density.

The sludge produced in the plant is recirculated for the pre-treatment of the raw acid feed for around 5 or 6 days or until a sludge density of 30 - 35 wt.% solids is achieved in the thickener tank. This is empirically determined by increased torque load on the thickener rake. A batch of the high density sludge is then discharged from the thickener for about 8 hours and pumped to the sludge drying ponds to allow for evaporation of residual water.

Most of the modification to the existing plant was completed at minimal cost. Aeration of the reactors required the purchase of an air blower while conversion of the plant to HDS mode required the redirection of a number of pre-existing pipes.

New plant

In May 2005, a second parallel series of 3 larger reaction vessels was installed to effectively double the treatment capacity of the plant (Fig. 7). This new plant also operates in HDS mode and has a design capacity of 25 kL/hour. The installation of the new plant and upgrade to the existing plant was completed at a cost of \$750,000 (AUD). Improvements in sludge density and settling characteristics enabled the existing thickener to accommodate the sludge output of both plants.



Figure 7. New treatment plant showing second parallel series of reaction vessels (upper left) with existing upgraded plant (lower right).

Commissioning of the new plant along with the upgrade of the existing plant has greatly improved the efficiency of reagent use. Recent estimates suggest that the volume of AMD treated per dry tonne of lime reagent is increasing and results also indicate an improvement in the water quality being discharged.

Sludge

Conversion of the existing plant to HDS mode has led to a reduction in the volume of sludge produced and costs savings in the order of \$30,000 (AUD) per annum related to the settling pond desludging requirements (Fig. 8). Sludge from the thickener / clarifier is now being produced at up to 42 wt.% solids with the HDS process in comparison to 3-5 wt% prior to the upgrade of the existing plant. This equates to a reduction of greater than 50% in the total volume of sludge produced.

Examination of the treatment sludge indicates it is dominated by crystalline material (65-75%) of which gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the dominant phase (Raven and Keeling, 2000; Wollard, 2003 and Earth Systems, 2004). Other phases present include minor bassanite ($2\text{CaSO}_4 \cdot \text{H}_2\text{O}$), quartz (SiO_2) and calcite (CaCO_3).

When the plant was operating in LDS mode, the north and south sludge ponds located at the back of the tailings facility were dislodged every summer to provide space for the following years production of sludge. The increased sludge density, resulting from the HDS process and other plant modifications, will reduce the frequency at which these ponds are dislodged from

annually to every 2-3 years. This represents an estimated cost saving of between 50 and 66% on dislodging costs alone.



Figure 8. Sludge pond. Low-density sludge prior to plant upgrade partly fills one of the two sludge ponds (upper left). Sludge pond full of partially air dried sludge prior to desludging (upper right). High-density sludge entering the sludge pond after plant upgrade (lower left and right).

An additional benefit of the increased density of the sludge is less water is being pumped out to the sludge ponds. Estimates conducted by Earth Systems (2004), based on volumes of sludge produced and available sludge storage volumes indicated that substantial volumes of water within the sludge ponds are lost by means other than evaporation. This water loss is most likely due to infiltration through the walls and base of the sludge ponds. Given the sludge ponds are situated on top of the backfilled tailings facility, the water had been infiltrating into the tailing sand and contributing to the seepage from the base of the tailings embankment. An increase in sludge density and decrease in water in the sludge ponds is likely to reduce the volume of water seeping from the tailings embankment and therefore reduce the volume of water requiring treatment.

Potential on site applications for the sludge are being examined. Currently some of the treatment sludge is being successfully used as a growth medium or soil amendment. It is also being considered for use as a water shedding cover for the tailings facility.

Tailings

Rehabilitation and revegetation of the tailings facility commenced in 1987 with trials using a thin (30 to 50 cm) soil and rubble layer spread over the tailings. Each year several thousand native tube-stock seedlings have been planted. The vegetation has reduced surface erosion, improved the visual appearance, and provided habitat for native fauna. In addition to this the capping and revegetation of the tailings facility has acted as a store and release cover, forming an evapo-transpiration layer that serves to reduce the deep percolation of rain into the tailing sand. Moisture is temporarily held in the root zone of the plants and from there it evaporates or is drawn up into the vegetation. This has greatly reduced deep percolation and hence the quantity of acid seeping from the toe of the tailings embankment. Measurements of depth to ground water in boreholes recorded each year indicate that the tailings facility is continuing to dry internally. This is also confirmed by decreasing quantities of seepage measured at a v-notch weir below the tailings embankment.

Following the ongoing efforts of PIRSA staff to lower seepage from the tailings embankment, the seepage contributed only 50 wt.% (28,031 kL) and 25 wt.% (25,169 kL) of the total acidity load to the existing treatment plant in 2002 and 2003 respectively (Earth Systems, 2004). Tailings embankment seepage is likely to have contributed the majority of the acidity load arriving at the plant prior to decommissioning of ponds on top of the tailings facility and revegetation of its surface.

A great deal of the success of the revegetation program was due to the use of ‘biosolids’ from the annual clean out of Waste Water Treatment Plants and from daily truckloads of wet sludge cleared from local domestic septic tanks. The biosolids were spread thinly over the tailings facility surface, contributing to increasing soil cover and providing moisture, nutrients and bacteria necessary to invigorate healthy plant growth.



Figure 9. Aerial view of the progressive rehabilitation of the tailings storage facility. Far left: 1973, 12 months after closure of the site. Middle: 1985, remaining acid water on tailings facility after initiation of treatment in 1980. Right: 1997, revegetated surface of the tailings facility.

Waste Rock

The third stage in the rehabilitation works at the Brukunga site involves the reduction of acid generation and seepage on site. The key to this will be the rehabilitation of the waste rock piles on site. Currently waste rock piles are located along the base of the open cut bench and have not been capped. This allows uncontrolled infiltration of water into the piles, and results in seepage of acidic drainage generated within the piles (Fig. 9).



Figure 9. Waste rock piles at the Brukunga site, to be rehabilitated during Phase 3 of the remediation program.

A number of options are being considered for rehabilitation of the waste rock piles. These range from capping of the existing piles to completely relocating the waste rock, either on or off site. A proposal is currently being considered to relocate the 8 Mt of waste rock back to the open cut and blend it with imported limestone marl. At present, cost estimates place this option at \$3M/year (AUD) over 7 years. On completion of the waste rock relocation and remediation, it is envisaged that acid seepage from the mine site will significantly diminish, resulting in greatly reduced ongoing treatment and maintenance costs.

Summary

Rehabilitation and treatment plant upgrade works have significantly improved the water quality downstream of the Brukunga mine site, dramatically reducing the off site risks associated with acid generation on site. In the process, upgrade of the AMD treatment plant from a Low Density Sludge to a High Density Sludge system, has resulted in significantly reduced costs (>50% ie. \$30,000 (AUD) per annum) associated with sludge handling and disposal. Recent estimates also suggest improvements in reagent efficiency, with a higher volume of AMD treated per tonne of lime reagent used.

Future rehabilitation plans are now focussing on reducing ongoing treatment costs further by lowering the acid load entering the plant. This is being addressed by plans to relocate and cap the exposed waste rock piles and continue to revegetate the site.

Acknowledgements

The authors would like to thank Primary Industry and Resources South Australia (PIRSA) for permission to publish this material.

Acronyms

AMD	Acid and metalliferous drainage
AMDEL	Australian Mineral Development Laboratories
ANSTO	Australian Nuclear Scientific and Technology Organisation
AUD	Australian dollars
AN905MPM	Specific type of advanced polymer flocculent
BMSRB	Brukunga Mine Site Remediation Board
CFS	Country Fire Service
EC	Electrical Conductivity
EWS	Department of Engineering and Water Supply
HDPE	High-Density Polyethylene
HDS	High Density Sludge
LDS	Low Density Sludge
ORP	Oxidation-reduction potential
PIRSA	Department of Primary Industries and Resources South Australia

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