CONTROLLING ACID AND METALLIFEROUS DRAINAGE FROM DECOMMISSIONED UNDERGROUND MINES

N. Bourgeot[A], J. Taylor[A], A. Sampaklis[B], N. Staheyeff[B], S. Pape[A], E. Hardjo[A] and M. Quiatol[A]
[A]Earth Systems, 14 Church St., Hawthorn, VIC 3122, Australia
[B]NSW Department of Planning and Environment, 516 High St., Maitland, NSW 2320, Australia

ABSTRACT

Operating and decommissioned underground mines can contribute a substantial amount of acid and metalliferous pollution to waterways worldwide. The key sources of pollution include unsaturated sulfidic materials in void wallrock and backfilled waste rock. Potential management measures are limited to passive or active treatment in perpetuity, or the installation of pressure bulkheads. Bulkheads are designed to facilitate flooding of the sulfidic materials to halt acidity generation, but are prone to chronic and catastrophic failure.

An alternative strategy has been developed and is currently being implemented at two decommissioned, polluting mine sites in New South Wales (NSW), supported by the Derelict Mines Program of the NSW Department of Planning and Environment. The sites are the Nevada Au mine and the Sunny Corner Ag-Pb-Zn mine, both located in the Daylight Creek catchment near the township of Sunny Corner. The strategy involves a two-stage process to remove oxygen from mine void atmospheres and replace it with an inert gas phase. In the absence of oxygen, sulfide oxidation and acidity generation cannot proceed.

Stage 1 involves the identification and isolation of all significant air entry points into the mine void. This usually includes features such as shafts, adits, declines, stopes, glory holes, subsidence zones and drill holes. Air entry control works need to retard oxygen addition to the mine voids, but not prevent water discharge. Once air entry points have been managed with appropriate earthworks and materials, the oxidation of sulfides within the mine can passively decrease internal oxygen concentrations. If the rate of internal oxygen consumption exceeds the rate of oxygen resupply, then net reductions in acidity generation can occur. Acidity (pollution) reductions of around 60-70% are considered possible following Stage 1 air entry control works. Barometric pumping or the breathing of the mine due to changing weather fronts is the prime control on oxygen resupply to isolated mine voids. Hence, if required, Stage 2 works include the active injection of small quantities of an inert gas (e.g. nitrogen or carbon dioxide) into the mine void to overcome barometric pressure gradients that act to intermittently resupply the void with air (i.e. 20.9 vol.% O_2), during high pressure climatic events.

Early results from the Nevada mine already demonstrate a 60% reduction in the acidity (acid and metals) generated from the site within 6 months of completing Stage 1 works. Key water quality data including pH, EC, acidity and metal concentrations are presented and discussed. Stage 1 works have also been completed at the Sunny Corner mine, and a 50% reduction in acidity load has also been achieved to date. These results clearly demonstrate the major water quality benefits of the Inert Atmosphere Technology for lowering pollution discharges from decommissioned underground mines at low cost.

1.0 INTRODUCTION

Tens of thousands of operating and decommissioned underground mines worldwide are ongoing sources of acid and metalliferous drainage or acid rock drainage (AMD/ARD) pollution. The key sources of pollution in recent and historic underground mines include unsaturated sulfidic materials in void wallrock and waste materials such as sulfidic waste rock and tailings that are often backfilled in the mine voids to facilitate mining or waste disposal. Sulfidic waste rock, rather than wallrock, is most commonly the primary source of AMD in underground mines (DIIS, 2016).

Many decommissioned underground mine sites are in remote areas and are left to pollute receiving waters with AMD due to the lack of cost effective solutions. The two key management measures are the installation of pressure bulkheads to flood reactive sulfidic materials and the active treatment of the AMD in perpetuity. These measures tend to be adopted only at a limited number of sites, where pollution generation is affecting sensitive receiving environments.

Pressure bulkheads are being used increasingly in coal mines, where the hydraulic heads are relatively low. The catastrophic failure of pressure bulkheads is limiting their uptake and increasing the requirement for improved engineering designs, improved construction methods and ongoing monitoring (Harteis et al., 2005; Mutton and Remennikov, 2011). In general, pressure bulkheads are regarded as moderate cost, relatively high risk and only moderate success structures. In comparison with pressure bulkheads, water treatment in perpetuity is normally regarded as a relatively high cost, low risk and high success management strategy.

2.0 INERT ATMOSPHERE TECHNOLOGY

A new low-cost, low risk and high success approach to lowering or preventing AMD from underground mines has been devised by Earth Systems to address the short-comings of the limited management options outlined above. This new approach is based on leading practice “atmosphere control technology” that aims to remove oxygen from mine void atmospheres and replace it with an inert gas phase. This technology was first introduced as a reducing atmosphere technology by Taylor and Waring (2001). In the absence of oxygen, sulfide oxidation and acidity generation cannot proceed. The mine void gas composition is controlled via a two-stage process:

- Stage 1: Identification and treatment of all significant air entry points into the mine void, including features such as shafts, adits, declines, stopes, glory holes, subsidence zones and drill holes. This Stage aims to passively lower oxygen concentrations within the mine due to oxygen consumption from internal pyrite oxidation. Air entry control works need to retard air re-supply to the mine void, but not prevent water discharge.

- Stage 2: Active injection of small volumes of an inert gas (e.g. nitrogen or carbon dioxide) into the mine void to overcome leakage or barometric pressure gradients that act to intermittently resupply the void with air (i.e. 20.9 vol.% O_2), during high pressure weather events.

Following the air entry control works, the initial control on void oxygen concentrations is provided by the sulfidic materials within the void. As long as the rate of oxygen consumption by sulfidic waste exceeds the rate of oxygen re-supply through the mine air entry control structures and fractured rock carapace surrounding the mine, then net reductions in acidity generation can occur passively. The extent to which this can happen is expected to be a function of:

- The mass of unsaturated sulfidic material in the void, including wallrock and backfilled material.
- The pyrite concentration (wt.% FeS_2) and pyrite oxidation rate (POR, wt.% FeS_2 / year) of unsaturated sulfidic material backfilled in the void.
- The depth of air entry into unsaturated, in situ sulfidic wallrock material in the void, and hence the volume of void wallrock exposed to oxidising conditions.
- The relationship between POR and variables such as oxygen concentration, moisture content and void temperature, for both backfilled waste materials and in situ wallrock.
- Local geological and hydrogeological properties of materials surrounding the void, and the effectiveness of the air entry control works (Stage 1 program).
- Local rainfall and infiltration characteristics of the site, and/or the extent to which the mine void has been flooded.
- The extent of internal methane and/or carbon dioxide production from the anaerobic decomposition of structural timbers or coal seam gas, or the production of carbon dioxide via limestone neutralisation.
- Local pressure gradients and the associated extent of barometric pumping, or the “breathing” of the mine, due to changing weather fronts. This is considered to be the prime control on oxygen resupply to sealed mine systems.

The extent of barometric pumping, and other site-specific factors listed above, determines the requirement, if any, to proceed with Stage 2 works.

The inert atmosphere technology outlined above is currently being implemented at two decommissioned, polluting mine sites in New South Wales (NSW), supported by the Derelict Mines Program of the NSW Department of Planning and Environment. The sites are the Nevada gold mine (Earth Systems, 2017a) and Sunny Corner silver-lead-zinc mine (Earth Systems, 2017b) and are presented as case studies below, with early results illustrating the benefits of inert atmosphere installations and their potential application to numerous other polluting underground mines throughout the world.

3.0 CASE STUDY – NEVADA MINE SITE

The Nevada site is a legacy gold mine located in Central West NSW, approximately half way between Lithgow and Bathurst, near the town of Sunny Corner. The site is located on NSW State Forestry land, within the steep valley of Daylight Creek. Vehicle access to the site is generally limited to 4WD light vehicles, due to track condition, and there is no power, mobile phone reception or other services available on site. The site features a main adit and several remnant surface features from the historic operation. These include smelter pads, small waste rock and slag piles and old shafts and stopes.

Water discharge from the site occurs solely from the main adit (Plate 1) at a rate of 1-5 litres per minute. AMD is clearly visible in drainage from the main adit, having discoloured the riverbank immediately downstream. Prior to 2017, the drainage pH ranged from 3.0-4.0, with an electrical conductivity (EC) that peaked at ~2,400 µS/cm.

Plate 1. AMD from the main adit at the Nevada mine site, prior to remediation works.

Key components of the inert atmosphere system installation program at the Nevada mine site included:

- Site survey and earthworks to enable detailed investigation of the main adit.
- Air-entry and drainage system control works at the main adit.
- More extensive air-entry control works at other locations at the site, including a shaft and several subsidence fractures at the ground surface.
- Installation of monitoring equipment in the mine void to quantify void gas composition and internal pressure and temperature.

The earthworks fleet consisted of a 9-tonne excavator, 4 tonne front tipping dump truck and a 20-tonne dump truck. Most natural geological materials were sourced from a State Forestry quarry located on Bob's Creek Rd, approximately 7 km from the work area. Air entry control earthworks were conducted at six areas in total, three of which could be accessed via existing tracks, with temporary tracks established for the remaining three areas.

Earthworks at the main adit area revealed an opening approximately 1.5 metres high and 1 metre wide. The walls and roof of the drive were partially collapsed with no direct visibility into the workings beyond approximately 5 metres.

During excavation, some existing mine water was discharged from the adit and treated in-situ using hydrated lime. A trench was dug across the road and a water discharge control pipe was installed 10 metres into the void, with an outlet to the Daylight Creek river bank directly opposite the adit. The discharge pipe incorporated a U-bend to prevent air entry back into the adit via the pipe, and two access points for pipe maintenance if ferrihydrite precipitation becomes a flow restriction issue. Imported clay materials were blended with commercial bentonite to seat the adit discharge pipe and form the basis for the adit seal. Adit sealing works were capped with gravel armour to protect the adit entry earthworks from erosion.

Air entry control works were completed over shafts, stopes and subsidence cracks using a combination of local and imported materials. Prior to all engineering works, all loose surface material was removed to expose the opening, or bare rock surrounding the adit opening.

A 100mm diameter PVC pipe was installed into one of the larger subsidence cracks, approximately 8 metres upgradient of the main adit, prior to completing earthworks in this area. Monitoring instruments were installed in this pipe to measure and record the mine void gas composition (oxygen and carbon dioxide), temperature and pressure.

All sensors were mounted into a custom fabricated 75 mm PVC housing that permitted lowering of the sensor assembly into the 100 mm PVC pipe. The sensor assembly was connected via cable to an external data logger. All cable connections were made via hermetically sealed terminals to prevent gas leakage. All monitoring sensors and the dataloggers are powered by 12V DC batteries and enclosed within a steel, tamper-proof enclosures fitted onto a concrete pad (e.g. Plate 2).

A weather station installed at the Sunny Corner Mine site was used to provide local ambient climate data (i.e. rainfall, pressure, temperature, wind speed and wind direction) for the Nevada (and Sunny Corner) site. This instrument was connected to a data logger with cellular telemetry capability, with surge protection equipment installed to prevent damage from high voltage surges such as lightning strikes.

Baseline monitoring of the adit drainage water chemistry was conducted in January 2017, with follow-up monitoring conducted from April 2017 onwards (pH, EC, ORP and acidity monthly and major ions and metals every 2 months). Continuous monitoring of void gas composition and internal pressure and temperature data commenced in mid-2017. Monitoring will continue for 24 months to evaluate the performance of the air entry control works and to inform the need for Stage 2 inert gas injection works.

Figure 1 provides key pH, EC and acidity concentration data for the main adit drainage, before and after completing Stage 1 of the inert atmosphere system installation. Data collected in January 2017 represent baseline chemistry for the site. The key results include:

- A step-wise improvement in discharge water chemistry is evident following the air entry control activities. Since these works the acidity of adit discharge decreased by close to 70% from 1,240 mg/L $CaCO_3$ (17/1/17) to 360 mg/L $CaCO_3$ (25/9/17). The EC decreased by approximately 50%, from 3.0 mS/cm to 1.5 mS/cm, over the same period.

- There is a strong correlation between EC and acidity data. The relationship between pH and acidity is more complex, and often large changes in acidity are required to produce even small changes in pH.

Consistent with the results presented in Figure 1, most metals present in the water exhibited decreasing trends since January 2017. The largest decreases have been observed in iron (from 111 mg/L on 17/1/17 to 13.6 mg/L on 28/8/17) and zinc (from 475 mg/L on 17/1/17 to 174 mg/L on 28/8/17).

Plate 2: Gas monitoring instrumentation and enclosure typical of that at the Nevada and Sunny Corner mine sites.

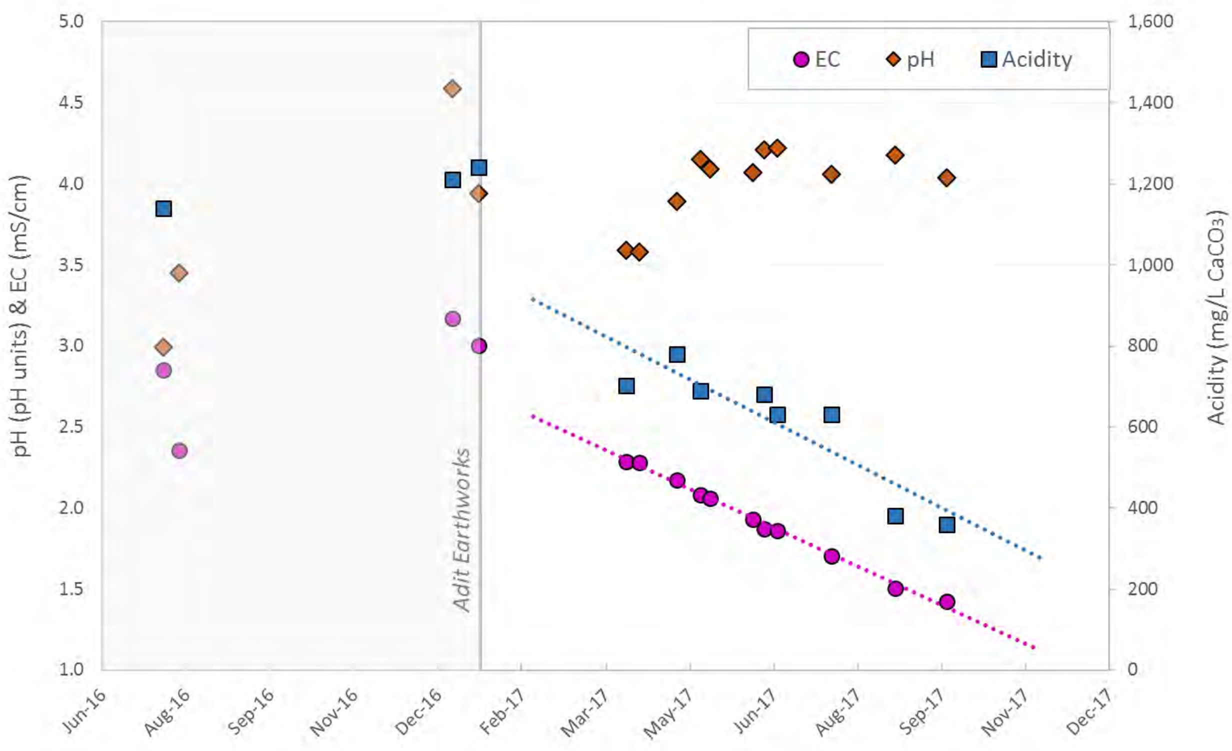

Figure 1: pH, EC and acidity data for the Nevada Mine site.

Key results from the void gas monitoring data reviewed to date indicate that:

- The mine void exhibits low oxygen concentrations and the rate of oxygen supply to the void is being substantially limited as a result of the earthworks program.
- Trends in oxygen concentrations appear to be associated with barometric pumping of air in and out of the workings. That is, when a low-pressure (climatic) system moves over the area, air is drawn out of the mine to equilibrate with the atmospheric pressure. Conversely, when the atmospheric pressure increases, air is forced into the mine void to equilibrate with atmospheric conditions.

The following conclusions can be drawn from the Nevada mine site case study to date:

- Following Stage 1 earthworks, the adit discharge water chemistry data is showing major decreases in pollution release the site. Clear decreasing trends in mine water discharge acidity and salinity are evident. Current acidity concentrations are close to 70% lower than baseline concentrations, and salinity concentrations have dropped approximately 50% over the same period. As expected, most metal concentrations have also decreased, particularly iron and zinc.
- The air entry and discharge control activities have resulted in the lower void oxygen concentrations that are responsible for rapid and sustained decreases in pollution from the site.
- Pollution concentrations are expected to decrease further; however some residual AMD is likely to persist from the site due to minor unavoidable air ingress via barometric pumping. An active inert gas generation system (Stage 2) would overcome this effect and prevent the residual AMD.

The results obtained to date provide clear validation that the inert atmosphere technology can substantially lower pollution from decommissioned underground mine sites.

4.0 CASE STUDY – SUNNY CORNER MINE SITE

A larger scale and more complex inert atmosphere installation is currently underway at the Sunny Corner mine site in NSW. Stage 1 works were completed in May 2017. This site also drains to Daylight Creek, approximately 2 kilometres upstream of the Nevada mine drainage confluence. Early monitoring results from the Sunny Corner mine site are very encouraging, indicating that:

- Oxygen concentration within the northern parts of the workings (near the main adit discharge point – Level 4 Adit) are significantly lower than atmospheric oxygen concentrations (3-10 vol.%). Some limitations on air re-supply to the southern parts of the workings are also evident in the water quality monitoring data.
- Flow rates from the Level 4 Adit (as measured via a v-notch weir) have decreased from ~1.5 L/s (November 2016) to ~0.7 L/s (June 2017), largely due to air entry control works (refer to Figure 2).
- Since completion of earthworks in May 2017, the adit drainage pH has been slowly increasing, and the salinity has been slowly decreasing over time, despite decreasing

flow rates. EC correlates well with acidity concentrations, reflecting small decreases in acidity over time. In the future, remotely-monitored continuous EC data (combined with pH and flow rates) could be used as the primary measure of rehabilitation success.

- A progressive long-term decrease in redox potential (Eh) of the mine drainage (700 mV in November 2016 to 510 mV in 25/9/17) appears to be consistent with observed decreases in oxygen concentrations within the void.

- The acidity load discharged from the Level 4 Adit has decreased significantly from approximately 60 tonnes H_2SO_4-eq per year (November 2016) to approximately 24 tonnes H_2SO_4-eq per year (August 2017) (refer to Figure 2). This decrease is considered largely attributed to the decrease in mine water discharge resulting from the air entry earthworks that are likely to have significantly altered the mine hydrology.

- A more delayed improvement in drainage water quality is expected at the Sunny Corner site, relative to the Nevada site, due to the substantially higher volume of stored AMD water that will need to be progressively flushed from the Sunny Corner mine void.

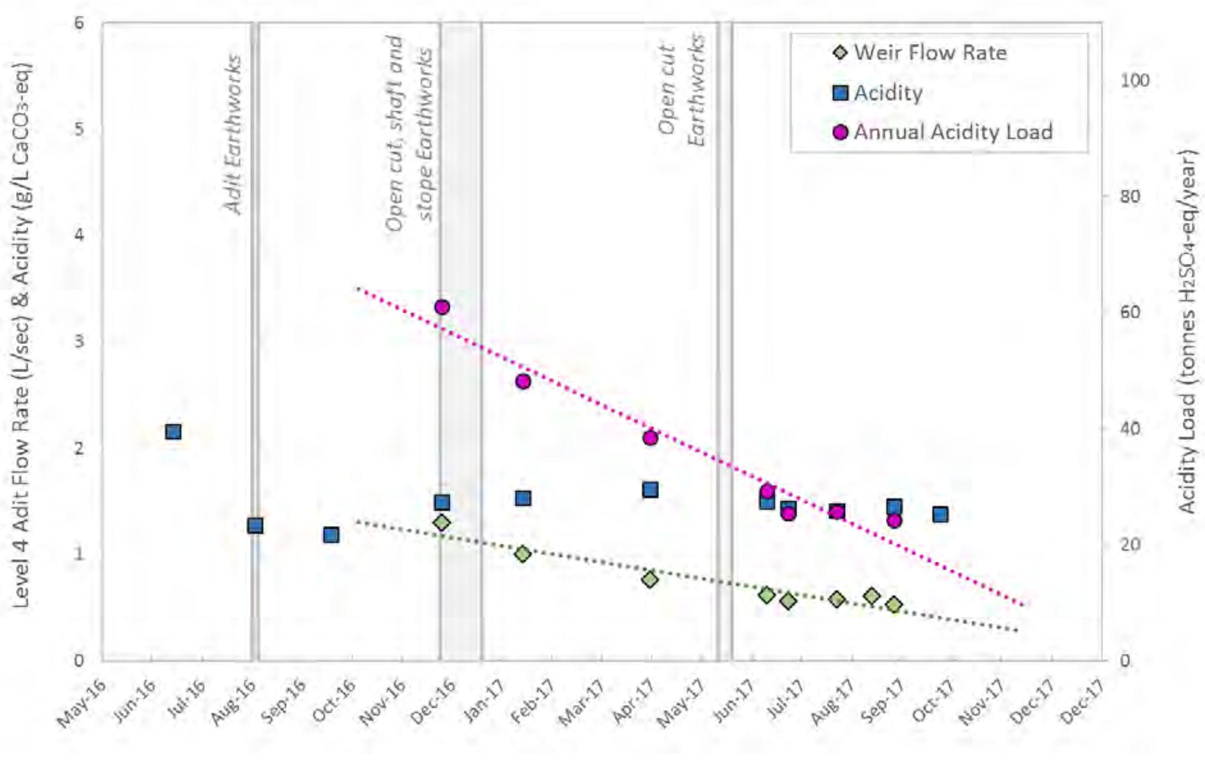

Figure 2: Level 4 Adit flow rate, acidity concentration and calculated annual acidity load equivalent from the Sunny Corner Mine site.

5.0 CONCLUSIONS

Substantial improvements in underground mine drainage water chemistry can be achieved in less than 3 months, with further improvements over time following the initial stage of an inert atmosphere installation, as highlighted by data from the Nevada mine site in NSW. Early results from the larger scale and more complex inert atmosphere installation at Sunny Corner are also very encouraging, but water chemistry improvements are slower. This is because there are significant volumes of stored AMD in the mine voids at Sunny Corner, retarding rapid improvements in the water chemistry and masking the apparent effectiveness of the air entry control works in the short term. However, at both sites the observed adit drainage quality improvements in such a short timeframe have exceeded expectations.

Monitoring results to date have already provided an improved understanding of key controls on the behaviour of mine void aqueous geochemistry and gas compositions at both sites. Additional monitoring data collected over the next 24-months will enable a more comprehensive evaluation of the performance of both Stage 1 inert atmosphere installations.

While further improvements in adit drainage water chemistry can be expected throughout this period, it is predicted that inert gas injection will be required to completely prevent AMD generation at both sites.

The broader implications of early results from the Nevada and Sunny Corner mine site case studies are that:

- Substantial reductions in pollution loads can be achieved from historic and temporarily decommissioned underground mines worldwide, by implementing strategic air entry and drainage control (Stage 1) works.

- AMD generation from underground mines can likely be fully prevented with inert gas injection installations, following the Stage 1 works.

- The cost of an inert gas injection system powered by renewable energy sources (e.g. wind or solar) is expected to dramatically lower the cost of managing AMD from underground mines relative to treatment in perpetuity.

- Inert atmosphere system installations offer a promising alternative to current treatment in perpetuity approaches for underground mine drainage. This approach will be substantially lower cost by avoiding the need for reagent manufacture and transport, full time personnel requirements and sludge management.

6.0 REFERENCES

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