Preventing Pollution from Underground Mines: Active and Decommissioned

Jeff Taylor¹, Nigel Murphy¹, Andrew Sampaklis² and Nick Staheyeff²

¹. Earth Systems, Australia
². Legacy Mines Program, New South Wales Department of Planning and Environment, Government of Australia

ABSTRACT

There are tens of thousands of derelict underground mines worldwide that are releasing acid, metalliferous and saline drainage into sensitive receiving environments. The primary source of the pollution is sulfidic waste rock that is used as backfill in the mine voids to facilitate mining. The widespread distribution of ventilation shafts ensures that advective processes dominate air entry into mine voids, and that there is effectively no limitation on air supply to the sulfidic wastes. While passive and active treatment systems are installed at a small number of mines, most sites continue to pollute.

The inert atmosphere technology has been developed and implemented at two decommissioned, polluting mine sites in Australia, with state government support. The technology can be implemented in either a one or two stage process, involving the partial or total removal of oxygen from mine void atmospheres, and replacement with an inert gas phase.

Stage 1 involves the mapping 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, highly fractured areas and drill holes. Air entry control works need to retard oxygen (air) addition to the mine voids, but not prevent water discharge. Once air entry points have been managed, the oxidation of sulfides within the mine passively lowers internal oxygen concentrations.

Case study results from the Nevada gold mine in New South Wales, Australia, clearly demonstrate the major benefits of the inert atmosphere technology for lowering pollution discharges from decommissioned underground mines at low cost and low risk. The success of this new technology also highlights the importance of incorporating key air entry and drainage control works into closure planning regulation for active underground mines worldwide.
INTRODUCTION

The uncontrolled discharge of acid and metalliferous drainage (AMD) or acid rock drainage (ARD) is occurring at many thousands of active and decommissioned underground mines worldwide. This pollution is derived from unsaturated sulfidic materials in void wallrock, sulfidic waste rock that remains underground and tailings that are sometimes used for backfilling. The rationale for using waste rock and/or tailings materials in underground mine voids is to facilitate mining or to assist with waste disposal. In either scenario, unsaturated, high surface area sulfidic materials in mine voids can create long-term AMD liabilities. At many of the older legacy underground mine sites, sulfidic waste rock, rather than wallrock, is the main source of AMD discharging from these sites (DIIS, 2016).

At remote sites, pollution from many decommissioned underground mines generally continues unchecked. The main management measures for underground mines include, (i) the installation of pressure bulkheads to flood reactive sulfidic materials, and thereby prevent oxygen access, or (ii) conduct active or passive treatment of the adit discharge in perpetuity. Such measures have only been implemented at a small number of environmentally or socially sensitive sites globally.

Pressure bulkheads are being increasingly used at coal mines, but only in situations where the levels of flooding (hydraulic heads) are relatively low. The potential for 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 & Remennikov, 2011). In general, pressure bulkheads are regarded as moderate cost, relatively high-risk and only moderate success structures. In comparison, water treatment-in-perpetuity is often regarded as a relatively high-cost, low-risk and high success management strategy. As the number of mine sites adopting water treatment-in-perpetuity increases, so too does the recognition that sludge management is a major long-term logistical, economic and social challenge.

This situation leaves the mining sector with a huge number of highly polluting sites with few simple, cost effective and low risk management options.

INERT ATMOSPHERE TECHNOLOGY

A new, low-risk, cost effective and high-success approach to lowering or preventing AMD from underground mines has been devised (Taylor & Waring, 2001; Bourgeot et al., 2017) to expand the number of management options. This new technology is based on controlling the gas composition in mine void atmospheres by passively, and if necessary, actively replacing oxygen with an inert gas phase. In the absence of oxygen, sulfide oxidation and hence pollution generation cannot proceed. This technology was first introduced as a reducing atmosphere technology by Taylor and Waring (2001) but has evolved into a more passive strategy that focuses on the establishment of inert gas atmospheres in mine voids. 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, fractured areas 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 aim to retard air re-supply to the mine void, but not prevent water discharge. No control is placed on void water levels or discharge rate. Maximum pollution reduction may not be possible with Stage 1 works only, as barometric pumping associated with climatic events cannot be passively prevented.

Stage 2: If maximum pollution reduction is necessary, active injection of small volumes of an inert gas into the mine void may be required to overcome leakage or barometric pressure gradients that act to intermittently resupply the void with air (ie. 20.95 vol.% O₂), during the passage of high pressure weather fronts.

Following Stage 1 air entry control works, the initial control on void oxygen concentrations is provided by sulfidic materials within the void. The same sulfidic materials that are responsible for water pollution from the mine can also be helpful in permanently lowering oxygen concentrations within the mine. For example, every 1 m³ of oxygen that is consumed in the mine void via sulfide oxidation is routinely replaced by 1 m³ of air, which contains only 20.95 vol.% oxygen. Therefore, 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 nitrogen concentration increases in the void atmosphere will occur via the net removal of oxygen. As oxygen concentrations decrease, reductions in pollution (acid and metal) generation will occur passively. The extent to which this can happen will be a function of:

- The mass of unsaturated sulfidic material in the void, including wallrock and backfilled material.
- The pyrite concentration (wt.% FeS₂) and pyrite oxidation rate (POR, wt.% FeS₂/year) of this sulfidic material.
- The relationship between POR and variables such as oxygen concentration, moisture content and void temperature, for both backfilled waste materials and in situ wallrock.
- The rate of oxygen re-supply to the mine voids, or effectiveness of the (Stage 1) air entry control works.
- Local geological and hydrogeological properties of materials surrounding the void.
- Extent of natural mine flooding.
- The nature and extent of internal gas production from the anaerobic decomposition of structural timbers, coal seam gas contributions, or the production of carbon dioxide via limestone neutralization.
- Local climatic conditions which will influence the magnitude of barometric pumping, or “breathing” of the mine, and affect oxygen re-supply rates.

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

The Inert Atmosphere Technology summarized here is currently being implemented at full scale at two decommissioned, polluting mine sites in New South Wales (NSW), supported by the Legacy Mines Program (LMP) of the NSW Department of Planning and Environment. The sites are the
NEVADA GOLD MINE CASE STUDY

Background

The Nevada gold mine is a legacy underground mine located in Central West NSW, approximately half way between Lithgow and Bathurst, near the town of Sunny Corner. The site is located in native forest bushland, within the steep valley of Daylight Creek. It comprises multiple air entry features, including 3 adits to 4 adits, 2 shafts and a stope to the surface (Figure 1), several waste rock piles, smelter pads and a slag pile. Vehicle access to the site is generally limited to 4WD light vehicles, due to track condition, and there is no power, cellular phone reception or other services available on site.

Figure 1 Stope to the surface and waste rock stockpile prior to air entry control program.
Figure 2  Drainage from main adit (prior to air entry controls) showing subsidence along initial part of adit.

Mine drainage is only discharging from a single adit (Figure 2) at a rate of 1 to 5 liters per minute. Prior to 2017, the drainage pH ranged from 3.0-4.0, with an electrical conductivity (EC) that peaked at ~2,400 µS/cm. Peak acidity values were as high as 1,240 mg CaCO₃/L. Key metals of concern included Fe, Al, Mn, Cu, Pb, Zn, Cd, Co and Ni.

REMEDIATION ACTIVITIES

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

- Feasibility assessment to clarify the likely benefits of an Inert Atmosphere Installation at this site.
- Based on a favorable outcome from the feasibility study, design and costing of air-entry and drainage control works.
- Implementation of air entry and drainage control works.
- Installation of void gas composition and internal pressure and temperature monitoring equipment in the mine void.
- Ongoing water quality monitoring of the adit discharge.

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. Air entry control works were completed for shafts, stopes and subsidence cracks using a combination of local and imported materials. Low permeability materials were sourced several kilometers from the site at a quarry and rock armor was locally sourced from waste rock materials. Specialist construction materials were sourced in the town of Bathurst. Conventional earthmoving equipment was used to facilitate the civil works.
Earthworks at the main adit area revealed an opening approximately 1.5 meters high and 1 meter wide. The walls and roof of the drive were partially collapsed with no direct visibility into the workings beyond approximately 5 meters. Some structural timbers were evident from the outside of the adit. No attempt was made to enter the adit. Drainage control works were installed within the adit to ensure that no increase in the drainage discharge level was created. A “u-bend” was installed near the outlet end of the drainage pipe to prevent the air flow back up the pipe and into the mine void.

**MONITORING DATA**

**Introduction**

Baseline grab-sample monitoring of the adit drainage water chemistry was conducted in January 2017, with follow-up sampling and analysis conducted from April 2017 onwards. Field based pH, EC, ORP and acidity monitoring were conducted on a monthly basis and a full laboratory analysis was conducted for major ions, soluble metals and acidity every 2 months. Continuous, datalogged monitoring of void gas composition (O₂ and CO₂), internal pressure and temperature commenced in mid-2017.

Gas sensors were mounted in a 75 mm PVC housing that permitted lowering of the sensor assembly down a 100 mm PVC pipe that was installed in the mine void. The PVC housing containing one oxygen sensor and one carbon dioxide sensor as shown in Figure 3. The sensor assembly is connected via cable to an external data logger. Cable connections from the sensor assembly to the data logger were hermetically sealed to prevent gas leakage. The gas monitoring sensors and the dataloggers are powered by 12V DC batteries and enclosed within a steel, tamper-proof enclosure bolted onto a concrete pad (Figure 4). The internal structure of the enclosures is shown in Figure 4B.

![Figure 3 Oxygen and Carbon Dioxide sensors within the gas sensor assembly](image-url)
Figure 4 Tamper-proof enclosure for gas sensor assembly (A) and related power, data logging and telemetry system (B)

Figure 5 Weather station with cellular telemetry

A weather station was installed at the top of a nearby hill to provide local ambient climate data, including rainfall, pressure, temperature, wind speed and wind direction, for the Nevada site (Figure 5). This instrument was connected to a data logger and was provided with cellular telemetry capability. Surge protection equipment was also installed to prevent damage from high voltage surges such as lightning strikes.

**Water Quality**

Figure 6 provides key pH, EC and acidity concentration data for the main adit drainage, before and after completion of the Stage 1 Inert Atmosphere Installation. Data collected up until January 2017 represents baseline chemistry for the mine.

Figure 6 shows a step-wise improvement in discharge water chemistry following the air entry control activities. Following these works, the acidity of adit discharge has decreased by 80% from 1,240 mg/L CaCO₃ (17/1/17) to 195 mg/L CaCO₃ (6/6/18). The EC decreased by approximately 75%, from 3,500 μS/cm to 850 μS/cm over the same period.
Highlighting the results presented in Figure 6, sulfate and most metals present in the water show consistent decreasing trends since January 2017. Sulfate concentrations have dropped from 2,450 mg/L in 1/17 to 470 mg/L on 6/6/18 (Figure 7A). This major decrease is consistent with substantial retardation of sulfide oxidation processes. The largest metal decreases have been observed in zinc from 475 mg/L on 17/1/17 to 77 mg/L on 6/6/18, and iron from 111 mg/L on 17/1/17 to below the detection limit of 0.05 mg/L on 6/6/18 (Figure 7B). Similar decreases in soluble metal trends are also evident for Al, Cu, Mn, Cd, Co and Ni (Figures 7C-7E). Indeed, only Pb exhibits no clear trend over the 18 months (Figure 7D). As there are no known carbonates in the mineralized system at Nevada, decreases in Ca and Mg ions over time (Figure 7F) are believed to reflect a decrease in silicate dissolution associated with a general decrease in acidity generation.

**Void Gas Composition**

Figure 8 provides a plot of void pressure, atmospheric pressure and void oxygen concentrations, all as a function of time. The void and ambient pressures appear to be different, but these readings are indistinguishable when the elevation difference between the two pressure sensors is taken into account. Despite the lack of a detectable pressure gradient, oxygen concentrations within the mine void have been steadily decreasing since the initial air entry control works. Current void oxygen concentrations are close to 7 vol.%. Recent carbon dioxide concentrations of at least 10 vol.% have also been recorded. Since no carbonate minerals are known to occur at the site, the carbon dioxide is likely related to the anaerobic decomposition of structural timbers.
Figure 7(A-F) Soluble metal concentrations over time from the main adit discharge at Nevada gold mine.
CONCLUSION

The Inert Atmosphere Technology demonstration at the Nevada mine site has provided the following insights relevant to the remediation of underground mines with AMD issues worldwide:

- Air entry and discharge control activities can result in sustained low void oxygen concentrations that are responsible for rapid and continuous decreases in site pollution.
- An 80% reduction in acidity (acid and metals) and a 75% reduction in EC can be achieved over an 18-month period.
- Monitoring data at the Nevada site provides a clear “proof-of-concept” that the Inert Atmosphere Technology can substantially lower pollution loads discharging from underground mines.
- Inert Atmosphere Systems offer a low complexity, low risk and cost-effective alternative to hydraulic seals and water treatment-in-perpetuity for underground mines.
- An Inert Atmosphere System could be completely passive at some sites, if air entry and drainage controls alone (Stage 1 works) are sufficient to lower AMD generation to acceptable levels.
- At some sites, Stage 1 works could provide a walk-away solution to chronic AMD.
- Stage 1 works should lower acidity discharges sufficiently to manage residual loads with passive treatment systems at many sites.
- Stage 1 works could dramatically increase the design life of passive treatment systems.
Implementation of an Inert Atmosphere System will be important for stopping AMD at treatment-in-perpetuity sites, where preventing costs and avoiding the production of sludge are high priorities.

The cost of a Stage 2 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.

Remote monitoring of sites subjected to Stage 1 or Stage 2 works greatly simplifies the management of chronic pollution issues.

The technique can be applied to the closure of recent or historic underground mines and probably quite safely to the unused portions of active mines.

Mining can easily resume as the approach is rapidly reversible.

Air entry control works have the potential to lower net percolation into mine voids and hence may simultaneously lower water discharge rates while improving discharge water quality.

Air entry control works will substantially lower public safety risks associated with accidental or unauthorised entry into mine workings.

Air entry and discharge control works will have a relatively low impact on site heritage values.

Closure planning for new underground mines worldwide should specify the installation of Stage 1 works for an Inert Atmosphere Installation.

REFERENCES


