7th International Conference on Acid Rock Drainage
ICARD – Abstracts

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March 26-30, 2006
St. Louis, Missouri

Richard I. Barnhisel, Editor

This meeting also serves as the

23rd Annual Meetings of the American Society of Mining and Reclamation
3134 Montavesta Rd.
Lexington, KY 40502
VIEWING PROCEEDINGS ABSTRACTS

The abstracts occur, for the most part, as single pages in order of the primary author’s last name or the author who presented the papers at the ICARD sessions in the meetings in March in St. Louis. The CD has 240 papers and abstracts and over 2700 pages of single page text.

Hint, you may wish to turn on the navigation under view toolbars to allow you to rapidly return back to the index of the cover page you had previously opened.

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MINE WATER MANAGEMENT IN EUROPEAN ENVIRONMENTAL POLICY: AN ASSESSMENT OF RECENT LEGISLATIVE DEVELOPMENTS

Jaime M. Amezaga; Paul L. Younger

Abstract. Since its creation, the European Union (EU) has developed a substantial amount of environmental legislation in the form of directives, regulations and decisions which are applicable to all the Member States. However, mining policy in the EU has been driven mainly by industrial considerations: the energy extractive industry being covered by the Directorate General Transport and Energy (DG TREN) and non-energy by DG Enterprise. For historical and economic reasons mining had been specifically excluded from much of the environmental policy developed by DG Environment. In the aftermath of the Baia Mare accident, the European Commission created a Task Force that proposed a plan of action with ideas for new legislation. They included the amendment of the Seveso II Directive and the production a document on Best Available Techniques (BAT) for the environmental control of mineral processing, similar to those produced under the Integrated Pollution Prevention and Control (IPPC) Directive. The main policy development has been a new Directive on the management of waste from the extractive industry, currently under discussion and expected to be approved in 2005. This article reviews the coverage of mine water in European legislation before and after these recent legislative changes from the point of view of the Water Framework Directive. Six critical issues are identified: the need to cover energy and non-energy industries, full life-cycle approach, mine water in the BAT document, mine voids in the mine waste initiative, abandoned mines and the whole catchment approach. The conclusion is that although the new policies constitute a substantial improvement in the regulatory framework of the EU, they address only some of the key issues. In particular, the full life-cycle and catchment approaches have not been sufficiently taken into account by legislators.

Additional Key Words: Water policy, waste management, extractive industries, European Directive

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Abstract. Reclaimed surface coal mines in the eastern United States are commonly revegetated with grasses and legumes. The productivity and carbon sequestration potential of the vegetation varies with the condition and nature of the mined site and soil. This study was conducted to determine the distribution pattern of soil carbon stock on 9 mined grasslands reclaimed after the passage of SMCRA in 1977. Mine soil samples of the surface and the subsurface overburden material were collected to approximately 2m depth and chemical and physical soil properties were determined on the less-than-2mm fine sample fraction. Results are presented for the vertical distribution of soil organic carbon concentration (SOC$_{C wt\%}$), fine earth (<2mm particle size) fraction (Fines$_{vol\%}$), coal-derived carbon concentration (Coal$_{C wt\%}$), and the bulk density of the fine earth fraction (BD$_{fines, g \, cm^{-3}}$) down the mine soil profile. The SOC$_{C wt\%}$ ranged between 0.0 and 0.767% and the Coal$_{C wt\%}$ ranged between 0.0294 and 4.53% among all samples. The $R^2$ of the soil organic carbon content (SOC) predictions (g C m$^{-2}$) was estimated at 60.6% and the shape of the prediction model resembled that of an exponential function. The results for a hypothetical scenario indicated that at an assumed cost of $24 per 1cm thick spoil layer across 1 hectare of homogenous project area, labeled as cost of SOC analysis within the soil profile, and $97.4 per Mg of elemental C, labeled as C credits for the analyzed SOC the maximum cost effective sampling depth was 48cm. One third of the total sequestered SOC was located beyond the cost-effective sampling depth for this experiment based on these sample analyses.

Additional Key Words: soil organic carbon, coal derived carbon, sampling depth, regression models, cost analysis

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PERFORMANCE OF THE ACID ROCK DRAINAGE MITIGATION WASTE ROCK TRIAL DUMP AT GRASBERG MINE

Judy Andrina, G.W. Wilson, Stuart Miller, Andrew Neale

Abstract. PT Freeport Indonesia constructed a large trial waste rock dump as a part of acid rock drainage (ARD) Management Program in 1999. The purposes of constructing the trial waste rock dump were to observe physical and geochemical behaviors of field-scale waste rock dumps, and to investigate oxidation and leaching behaviors in order to optimize dump design for ARD mitigation. This paper presents the analysis and results of data collected during the 4-year test period. Results suggest that variations in oxygen and temperature profiles observed within the trial dump panels depend on the type of waste rock, particle size distribution and dumping methods. The placement of coarse rock layers was observed to promote oxygen transfer into the waste rock dump. Barometric pressure did not vary significantly between the atmosphere and the interior of the dump. The application of an impermeable surface cover was observed to have only a limited effect on oxygen concentrations within the profile of the waste rock. All of these findings support the hypothesis that advection of air flow through the coarse rock / rubble zone at the base of the dump is a primary pathway for oxygen transport in Grasberg waste rock dumps. The information gathered during the present field-scale investigations will be used to establish optimum dump designs for long-term closure issues and ARD management.

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SURFACE MINE REFORESTATION RESEARCH: EVALUATION OF TREE RESPONSE TO LOW COMPACTION RECLAMATION TECHNIQUES¹

Patrick N. Angel, Donald H. Graves, Christopher Barton, Richard C. Warner, Paul W. Conrad, Richard J. Sweigard, Carmen Agouridis²

Abstract. In 1996, a multidisciplinary group of researchers at the University of Kentucky initiated a study on the Starfire surface mine in eastern Kentucky to evaluate the effects of soil compaction and two organic amendments on the survivability and growth of high value tree species. Three types of prepared rooting medium were examined: compacted spoil, lightly compacted spoil, and uncompacted spoil. The compacted spoil was prepared using normally accepted spoil handling techniques that resulted in a smooth graded surface. The lightly compacted spoil was loose-dumped and struck-off with one or two passes of a bulldozer. The uncompacted spoil was loose-dumped and not further disturbed. In addition, organic amendments (mulches) were evaluated within the three reclamation techniques. The organic amendments used were processed hardwood bark mulch and a combination of straw and horse manure mulch. The following six species of trees were planted: white oak (Quercus alba), white ash (Fraxinus americana), eastern white pine (Pinus strobus), northern red oak (Quercus rubra), black walnut (Juglans nigra), and yellow poplar (Liriodendron tulipifera). Five of the six species, the exception being white ash, showed increased survivability as compaction was minimized. Additionally, the loose-graded techniques led to enhanced growth in height for the seedlings. The addition of organic amendments also showed additional benefit but results varied by species and by treatment. Results definitively show that strike-off and loose-dump techniques improve seedling height and survival. The data also suggest that even a small amount of traffic (i.e., one or two passes per the strike-off method) may result in enough compaction to significantly reduce survival and growth in some species, such as yellow poplar and white pine. In the backfilling and grading process, spoil material should be placed and compacted according to standard engineering practices so that the required stability and approximate original contour is achieved. However, the top 1.2 to 1.8 meters (4 to 6 feet) of material should not be graded or only lightly graded so that it is as uncompacted as possible.

Additional Key Words: tree performance, compacted spoil, mulches, high-value hardwoods.

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INCORPORATION OF NATURAL SLOPE FEATURES INTO THE DESIGN OF FINAL LANDFORMS FOR WASTE ROCK STOCKPILES

B. Ayres, B. Dobchuk, D. Christensen, M. O’Kane and M. Fawcett

Abstract. Historically, final landforms for waste rock stockpiles consist of linear (in plan), planar slope surfaces with unvarying gradients and angular slope intersections. Slope drainage structures are generally oriented along contours and are highly engineered, while revegetation efforts follow artificial configurations. By contrast most natural slopes are characterized by a variety of shapes (typically concave), and drainage systems follow natural drop lines with catchment sizes defined by undulating relief on the slope. Vegetation on natural slopes grows in discrete vegetation units that are adjusted to hillside hydrogeology, incident solar radiation, and other microclimate effects.

This paper reviews the key elements of natural slopes and proposes methodologies for improved design of final landforms, and in particular, methodologies for the reclaimed slopes of waste rock stockpiles. Two case studies are included to demonstrate that natural slope configurations are more stable than highly engineered landforms over the long term. The design methodologies and supporting discussions presented in this paper are also applicable to any above-ground waste storage facility with topographic relief.

Additional Key Words: Landform evolution, geomorphology, SIBERIA, WEPP, mine rehabilitation

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REMEDIATION OF ACID MINE DRAINAGE IN THE SUGAR CREEK WATERSHED, MISSOURI: TECHNOLOGY AND COSTS FOR USE IN TMDL ASSESSMENT¹

Paul T. Behum² and Eric D. Christensen²

Abstract. The Sugar Creek Watershed is located north of Huntsville in north-central Missouri. Water quality in Sugar Creek has been affected by acid mine drainage (AMD) generated by underground mining and coal refuse disposal before the Surface Mining Control and Reclamation Act of 1977 and has been listed on Missouri’s 303d list as an impaired stream. To support the state of Missouri’s development of a Total Maximum Daily Load (TMDL) assessment and remediation efforts, the Office of Surface Mining (OSM), Mid-Continent Region in cooperation with the U. S. Geological Survey (USGS), Missouri Water Science Center - Kansas City Office has completed a technical evaluation and economic and logistical feasibility study for the AMD affected waterway. Utilizing a water-quality assessment completed in 2005 by the USGS, the OSM study proposes the construction of passive treatment facilities for three major AMD sources identified by the USGS in the watershed. Site-specific remediation costs are determined for each site using OSM’s Technical Innovation and Professional Services software AMDTreat. The proposed treatment systems utilize state-of-the-art passive treatment technology, including anaerobic bioreactors and vertical flow wetlands. Treatment of the discharges from two of the AMD sources add alkaline effluent from public waste-water treatment facilities for neutralizing acidity, dilution of the AMD, and addition of nutrients into the proposed wetland treatment systems. This study will be used to develop costs and a plan for the remediation of the Sugar Creek discharges and can serve as a guide in TMDL assessments in Missouri and other coal mining areas.

Additional Key Words: passive treatment, aerobic wetland anaerobic bioreactor, and vertical flow pond.

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IMPLEMENTATION OF PASSIVE TREATMENT OF ACID MINE DRAINAGE (AMD) IN THE MID-CONTINENT REGION: THE LE BOSQUET CLEAN STREAMS PROJECT

Paul T. Behum, Geoffrey A. Canty, and Robert W. Nairn

Abstract. Several new passive treatment systems have been constructed to treat acid mine drainage (AMD) in the Mid-Continent Region. This poster discusses the construction and preliminary results of one new site—LeBosquet 064 2004 Clean Streams Reclamation Project. As a part of ongoing technical assistance with the Oklahoma Conservation Commission’s (OCC) Abandoned Mine Lands Program, the Office of Surface Mining (OSM), Mid-Continent Region (MCR) assisted in the design and evaluation of the treatment system. The project site was an artesian seep located 4 miles (5 km) west of the town of Fanshawe, in LeFlore County, Oklahoma. Preliminary water quality results indicated that the combination of an anoxic limestone drain system and a surface flow treatment wetland has been effective at mitigating the adverse impact associated with the AMD.

Additional Key Words: anoxic limestone drain, surface flow treatment wetland.

Problem. An artesian AMD seep, located approximately 4 miles (5 km) west of Fanshawe, Oklahoma, (Fig. 1) discharged into Cedar Creek resulting in adverse water quality impacts. OSM-MCR and OCC collected pre-construction water quality data (Table 1) that showed that the discharge was characterized by elevated iron (34 mg/L), decreased pH (5.11 S.U.), and net acidic (90 mg/L as CaCO_3) conditions. Once the seep discharged reached the receiving environment, the AMD oxidized resulting in a 0.5 acre “kill zone” devoid of vegetation (refer to Fig. 2). The runoff also adversely affected Cedar Creek. Cedar Creek is considered a warm water aquatic community and is used for agricultural purposes. The seep discharge has impaired the beneficial uses of the creek, and may be contributing to degradation of the downstream reservoir – Lake Wister.
ADDRESSING ACID DRAINAGE IN THE AUSTRALIAN MINERALS INDUSTRY

L. Clive Bell

Abstract. The national survey of the extent of acid drainage (AD) conducted in 1997 confirmed that AD was a significant environmental issue for the Australian minerals industry. The recommendations arising out of that survey served as a basis for actions by government, industry, industry-support organisations such as the Australian Centre for Minerals Extension and Research (ACMER) and other research organisations to enable more effective prevention and management of AD.

This paper documents the extent of AD in the industry, the government regulations and guidelines for AD management, industry initiatives, the role of ACMER and other organisations in assisting industry through research and technology transfer, and the efforts being made to deal with AD at abandoned mines.

Management of AD in the industry is being assisted by the linkage of Australia (through ACMER) into the International Network for Acid Prevention (INAP) Global Alliance which is facilitating the interchange of knowledge on AD as well as coordinating global research on the topic.

Additional Key Words: regulation, research, technology transfer, abandoned mines.

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ENVIRONMENTAL MANAGEMENT PLANS: A KEY TOOL IN ENSURING SUCCESSFUL LONG-TERM ENVIRONMENTAL MANAGEMENT AT CLOSED MINE SITES WITH ML/ARD

Kim Bellefontaine and William Price

Abstract. Mines with metal leaching and acid rock drainage (ML/ARD) often require long-term mitigation, monitoring and operator vigilance to ensure environmental protection. One of the biggest challenges to meeting long-term environmental protection goals is retaining the collective corporate, regulatory and community memory of site conditions, history of mining activities and mitigation requirements for the site. An Environmental Management Plan (EMP) can help ensure successful management by documenting key aspects of a mine site, as well as its mitigation, monitoring and maintenance requirements. EMPs are intended to be living documents that track important changes for the purpose of guiding site management decisions. EMPs are being developed for several mines in British Columbia, Canada and include items such as active chemical treatment and cover maintenance.

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SCALE UP EFFECTS ON MASS LOADING RATES IN AN ARID ARCTIC ENVIRONMENT

Valérie Bertrand, Preeti Anand, Rens Verburg, and Craig Goodings

Abstract. The Meadowbank Gold Project of Cumberland Resources Limited is located 70 km north of Baker Lake in the arid, arctic environment of Nunavut Territory, Canada. With a site annual average temperature of -11°C, and 310 mm/year precipitation, the extrapolation of constituent loading rates from laboratory tests is particularly precarious. Three different scales of kinetic leaching tests were performed on waste rock samples: 1-kg and 100-kg laboratory leaching cells and 250-kg field cell tests.

Field tests yielded considerably slower rates of buffering capacity depletion and sulfide oxidation than laboratory-derived rates, although the differences were not consistent between the various test scales.

Additional Key Words: kinetic test, buffering, sulfide oxidation

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INVESTIGATIONS INTO THE DEPTH AND RATE OF WEATHERING ON WITWATERSRAND GOLD TAILINGS DAM SURFACES AS KEY INFORMATION FOR LONG-TERM ARD RISK ASSESSMENTS

Nico Bezuidenhout¹, Pierre D.S. Rousseau²

Abstract. The generation of Acid Mine Drainage (AMD) from tailings dams of the Witwatersrand goldfields in South Africa, is arguably one of the main strategic environmental issues facing the gold mining industry and the South African government. Fine grained, sulfidic, tailings impoundments generate AMD through the diffusive ingress of oxygen into unsaturated pore spaces. Golder Associates conducted research on behalf of the Water Research Commission of South Africa to determine what the likely rate and depth of oxidation is within typical tailings impoundments of the Witwatersrand goldfields. Investigations consisted of a combination of literature research, field work and sulfide-oxidation modeling. The results of these investigations suggest that the bulk of a typical Witwatersrand tailings facility will acidify after hundreds to thousands of years of sulfide oxidation. Acidic drainage, however, may be generated within the wall and toe paddock sections during the operational phase or shortly after decommissioning and closure. The production of acidic drainage, therefore, can be mitigated during the operational phase.

Additional Key Words: Oxygen diffusion, tailings seepage, acidification, neutralization.

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MODELING OF GROUNDWATER INFLOW TO A LARGE OPEN-PIT IN LOW-PERMEABILITY MOUNTAINOUS TERRAIN

Mark Birch, Betsy Semmens, Leslie Smith, David Banton, and Ned Hall

Abstract. A regional-scale three-dimensional model was developed using MODFLOW-SURFACT to delineate the capture zone and groundwater flow regime associated with a large open pit mine situated in low-permeability mountainous terrain. In low-permeability mountainous settings, local-scale flow systems often develop between elevated terrain and local drainages. Accurate representation of these flow systems through robust handling of recharge and seepage across the land surface interface proved critical in representing the true three-dimensional nature of the pit capture zone. The approach further allowed for more accurate representation of recharge, discharge, and the directions of groundwater flow associated with stockpiles near the pit. Modeling results indicate that the pre-stockpile surface topography largely controls the direction of flow of recharged groundwater near the pit and the nature and extent of the pit capture zone. The pit capture zone is herein defined as the surface area over which particles released at the water table report to the pit. The modeling results further indicate that deeper groundwater from a larger area also discharges into the pit. With greater depth, the influence of the local surface topography dissipates, and the influence of the hydraulic sink associated with the pit increases, resulting in a transition of groundwater flow controlled by local surface topography to groundwater flow controlled by the pit.

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IMPACTS ON WATER QUALITY AND BIOTA FROM NATURAL ACID ROCK DRAINAGE IN COLORADO’S LAKE CREEK WATERSHED

David A. Bird, Matthew A. Sares, Greg A. Policky, Travis S. Schmidt, and Stanley E. Church

Abstract. Colorado’s Lake Creek watershed hosts natural acid rock drainage that significantly impacts surface water, streambed sediment, and aquatic life. The source of the ARD is a group of iron-rich springs that emerge from intensely hydrothermally altered, unexploited, low-grade porphyry copper mineralization in the Grizzly Peak Caldera. Source water chemistry includes pH of 2.5 and dissolved metal concentrations of up to 277 mg/L aluminum, 498 mg/L iron, and 10 mg/L copper. From the hydrothermally altered area downstream for 27 kilometers to Twin Lakes Reservoir, metal concentrations in streambed sediment are elevated and the watershed experiences locally severe adverse impacts to aquatic life due to the acidic, metal-laden water. The water and sediment quality of Twin Lakes Reservoir is sufficiently improved that the reservoir supports a trout fishery, and remnants of upstream ARD are negligible.

Additional Key Words: Grizzly, Lake, Chaffee, Twin Lakes, Arkansas River, trout, invertebrates

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CONSTRUCTION OF TWO LARGE-SCALE WASTE ROCK PILES IN A CONTINUOUS PERMAFROST REGION

David Blowes, Michael Moncur, Leslie Smith, David Sego, John Bennet, Andrew Garvie, Claire Linklater, Douglas Gould and Jeff Reinson.

Abstract. The discovery of diamonds in Canada’s North has led to renewed interest in the development of mining properties in the Arctic. At the Diavik Diamond Mine Inc. operation, open pit mining will lead to the construction of two 200 Mt permanent stockpiles of waste rock. A rigorous, quantitative framework for assessing the long-term environmental implications of storing waste rock in regions with continuous permafrost has yet to be developed. Our study involves the construction of two large-scale waste rock piles (15 m in height × 60 m × 50 m) to assess the evolution of the hydrology, geochemistry, temperature, and biogeochemistry of the waste rock piles over time. One test pile will contain rock with a sulfide content of < 0.04 wt% S and the other test pile contains rock with > 0.8 wt% S. Complementary studies involving conventional static and kinetic tests on small test samples have also been initiated. The results from this five-year study will assist mining companies and regulators in evaluating current waste rock pile designs. This paper describes the construction of test piles, preliminary modeling of heat transfer and oxygen transport within the piles, and additional testing planned to quantify the relationship between weathering rates in laboratory dissolution tests and those in waste rock piles in the field.

Additional Key Words: kinetic oxidation modeling, heat conduction, scale-up

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ON THE RELEVANCE OF MEROMIXIS IN MINE PIT LAKES

Bertram Boehrer and Martin Schultze

Abstract. Worldwide the number of mine pit lakes is growing. Due to their steep slopes, their relatively great depth and their exposure to highly mineralized inflows, a remarkable portion of these lakes tend to be meromictic. Meromixis indicates that the deepest part of the water body - the monimolimnion - is excluded from seasonal overturn and thus from contact to the atmosphere. Although this phenomenon is not common in natural lakes, it is well known. Meromixis is accompanied by some important consequences with respect to water quality: (1) strong anoxia in the monimolimnion, (2) enrichment of products of microbial decay in the monimolimnion and (3) occurrence of hydrogen sulfide and precipitation of metal sulfides in the monimolimnion. In some cases, advantage can be taken from the enrichment of substances in the monimolimnion due to the very low exchange with the rest of the lake. As a consequence, hazards may be avoided. On the contrary, if a sudden total overturn happens, e.g. induced by a heavy storm, fish kills and other catastrophic events may be the consequence.

Additional Key Words: management of water quality, remediation

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GROUNDWATER RESPONSE TO THE END OF FORTY YEARS OF COPPER HEAP LEACH OPERATIONS, BINGHAM CANYON, UTAH

Richard K. Borden, Vicky Peacey and Brian Vinton

Abstract. There are many mature Cu heap leach facilities in the western United States that will face closure in the next decade. However, there is little published information on the response of groundwater systems to the cessation of leaching. Copper dump leaching was conducted on the Bingham Canyon Eastside waste rock dumps between 1963 and 2000. Leach water discharging from the toe of the waste rock dumps had a typical pH of 2.9 and a total dissolved solids concentration of about 90,000 mg/L. During active leaching this water was recirculated, but now it is neutralized as it enters the mine’s tailings and process water circuit. With the end of leach water application, average annual flows discharging from the toe of the dumps have declined rapidly from 1500 L/s in 1998 to approximately 45 L/s in 2004. Average acidity in water discharging from the toe of the dumps declined by almost thirty percent between 2000 and 2005, and since 2003, most solute concentrations have declined by about ten percent. The only exception is Cu concentration which has increased by a factor of four since 2000. Water quality in the underlying saturated bedrock has also begun to improve. Since 2000, sulfate concentrations have declined by a third, alkalinity has increased, and Cu and Zn concentrations have declined by up to ninety percent in water from tunnels that receive at least a portion of their inflows from beneath the waste rock footprint. Water quality in bedrock and alluvium down gradient of the dump toe began to improve after the leach water collection system was upgraded between 1994 and 1996. Arithmetic mean sulfate concentrations in down gradient alluvial monitoring wells declined from a high of 6000 mg/L in 1994 to less than 1000 mg/L in early 2004. These data illustrate how the groundwater system responds to the termination of waste rock and heap leach operations and may provide a useful analogue for the closure of other Cu heap leach operations.

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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IN SITU TREATMENT OF METAL MINE TAILINGS USING EOS\textsuperscript{®1}

Robert C. Borden\textsuperscript{2}

Abstract: Ore Knob Branch and Peak Creek within the New River Basin of North Carolina are impaired due to discharge of acid mine drainage with high iron (200-250 mg/L), aluminum (3800-4300 μg/L), copper (220-690 μg/L) and zinc (780-1000 μg/L) and low pH (2.9-3.1) from a tailings impoundment at the former Ore Knob copper/zinc mine. Surface runoff and groundwater from the upstream watershed percolates through the tailings, discharging as a series of small springs or seeps on the dam face.

A pilot study is being conducted to evaluate the potential for in situ anaerobic bioremediation within the tailings impoundment. Edible oil substrate (EOS\textsuperscript{®}) will be injected directly into the tailings through a line of wells installed immediately upgradient of the embankment. EOS\textsuperscript{®} is prepared from a mixture of easily biodegradable substrates (lactate and amino acids) and more slowly biodegradable emulsified soybean oil. In the field, the concentrated oil-in-water emulsion is diluted with plain water and then injected using temporary or permanent wells. As AMD flows thought the treated zone, EOS\textsuperscript{®} stimulates rapid growth of iron and sulfate reducing bacteria, increasing the pH, reducing sulfate, and immobilizing iron, copper, nickel, zinc and related toxic metals. The slowly biodegradable soybean oil present in EOS\textsuperscript{®} provides a slow, steady supply of organic carbon to support long term treatment. All materials used in the process are Generally Recognized As Safe (GRAS), food-grade materials (21 CFR 184.1400) to aid in gaining regulatory approval for in situ application. Sufficient EOS\textsuperscript{®} will be injected to last five to ten years.

Laboratory studies have demonstrated that this approach can be very effective in treating AMD, resulting in a dramatic increase in pH, and reduction in dissolved metals. In laboratory columns packed with acid forming mine spoils and treated with emulsified soybean oil, the pH increased from less than 3 to ~ 6, SO\textsubscript{4} was reduced by 80%, aluminum dropped from ~100 mg/L to below detection (<0.02 mg/L), and both copper and zinc dropped from ~60 mg/L to below detection (<0.02 mg/L).

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} 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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THE USE OF BASIC OXYGEN STEEL FURNACE SLAG (BOS) AS A HIGH SURFACE AREA MEDIA FOR THE REMOVAL OF IRON FROM CIRCUM NEUTRAL MINE WATERS

Lawrence I. Bowden, Karen L. Johnson, Adam P. Jarvis, Howard Robinson, Nizar Ghazireh and Paul L. Younger

Abstract. Pilot scale reactors have been installed at a mine water pumping station in County Durham, UK, to investigate the potential of Surface Catalysed Oxidation Of Ferrous Iron (SCOOFI) for rapid removal of iron, using BOS as the treatment medium. The water is circum-neutral, with [Fe] in the range 2–5 mg/L, [Mn] 0.60 – 0.70 mg/L, and [SO₄] approximately 300 mg/L. Saturated flow reactors with residence times of approximately 20 minutes, and a range of BOS particle sizes (20 – 100 mm) have been used to establish the influence of surface area on removal efficiency and system longevity. Iron removal rates are in the order of 80% for all reactors. Differences between reactors, and the potential application of this type of passive treatment, are described in detail in the paper.

Additional Key Words: SCOOFI, Basic Oxygen Steel Slag, Iron Removal.

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PROTOCOLS AFFECTING THE REACTIVITY OF MINE WASTE DURING LABORATORY-BASED KINETIC TESTS

Bowell, R.J.\textsuperscript{2}, Sapsford, D.J\textsuperscript{3}, Dey, M.\textsuperscript{3}, and Williams, K.P\textsuperscript{3}

Abstract. This paper presents data from a number of humidity cell style weathering tests for the evaluation of ARD behaviour. These tests indicate that the results of such test work can be influenced by particle size, mineralogy, as well as the effects of aeration versus non-aeration; of sample mass; of flushing frequency; solution-mineral interaction in the cell and the duration of the testwork. The work undertaken to date indicates that many of the concerns and idiosyncratic details insisted in many protocols do not appear to have a significant impact on leaching rates. Far more important appears to be sulfide and secondary mineralogy; grain size and length of exposure to aeration.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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APPLICATIONS OF BIOLOGICAL H₂S PRODUCTION FROM ELEMENTAL SULFUR IN THE TREATMENT OF HEAVY METAL POLLUTION INCLUDING ACID ROCK DRAINAGE

Michael Bratty, Rick Lawrence, David Kratochvil, Brad Marchant

Abstract. BioteQ Environmental Technologies Inc. has developed and commercialized a high rate anaerobic biotechnology for on-site production of H₂S from elemental sulfur for low cost water treatment and sulfide reagent production. The process is demonstrated for mining and mineral process water treatment, including ARD treatment, with concurrent recovery of saleable metals and the reduction or elimination of toxic water treatment sludges. The production of H₂S takes place in a stand alone bioreactor, on demand, at ambient temperatures and pressures, minimizing on-site sulfide inventory, and thus improving the overall safety of the process. The main advantages of treating heavy metal pollution using biogenic H₂S are discussed and specific environmental and economic benefits are demonstrated using data from the existing commercial installations.

Additional Key Words: ARD, Sulfur Reduction, Metal Recovery, Water Treatment

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2 Michael Bratty, Rick Lawrence, David Kratochvil and Brad Marchant are Senior Project Engineer, Executive Vice President, Manager of Engineering and President, respectively, BioteQ Environmental Technologies, Inc., Vancouver, BC, V6C 2G8, Canada.
Abstract. The Savage River Mine has operated as an open cut iron ore mine on
the northwest coast of Tasmania since the mid 1960’s. The impact from ARD
became evident during the 1990’s when monitoring found high levels of Cu and
low pH in the river over 30 km downstream of the mine. Closure of the mine in
the mid 1990’s and subsequent reopening by new owners resulted in funding of
approximately A$24M for remediation to be administered by a joint committee
representing the mine owners and the Tasmanian state government.

Ecotoxicology work showed that Cu was not acutely toxic to aquatic life
forms provided alkalinity levels of more than 15mg/L and pH>6.5 were
maintained in the river. A feasibility study established methods of achieving
these goals by a range of measures including oxygen exclusion covers, water
shedding covers, ARD catch drains, pumping systems and use of centralized
treatment facilities. The utilization of naturally occurring magnesite and other
alkaline rocks was of particular interest. Capital and operating costs of possible
options were estimated to +/- 30% for comparison then a whole of site strategic
plan developed to demonstrate how the required level of remediation could be
achieved and maintained over a 60-year time span using the funds available.

The Strategic Plan showed the committee that the aims of remediation were
achievable and delivered a program that could be met by staged development
making effective use of the operating mine resources.

The paper describes the site, the strategic plan and details of the
implementation to date.

Additional Key Words: Savage River Mine, magnesite, acid drainage

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26-30, 2006, St. Louis MO. Published by the American Society of Mining and Reclamation
(ASMR), 3134 Montavesta Road, Lexington, KY 40502
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GEOCHEMICAL CHARACTERIZATION AND WATER QUALITY PREDICTION AT THE ANTAMINA MINE¹

David Brown ², Rens Verburg ³, Henri Letient ⁴, and Celedonio Aranda ⁵

Abstract. The Antamina mine, located in the Peruvian Andes, is one of the world’s largest operating copper-zinc mines. A comprehensive geochemical characterization program of waste rock and low grade/marginal grade ore has been underway to fulfill a number of objectives. These objectives focus on developing an understanding of potential operational and post-closure impacts to the environment, assisting with identification and implementation of prevention/mitigation measures, and refinement of the current waste rock management program. The geochemical characterization program follows a multi-faceted approach, including extensive long-term laboratory and field testing and operational monitoring. This presentation will provide an overview of the geochemical characterization program at Antamina, including relationships between results from laboratory testing, field testing and operational monitoring, and water quality modeling.

Additional Key Words: metal leaching, neutral drainage, waste rock, sulfide

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AIRBORNE GEOPHYSICAL SURVEY FOR MAPPING ACID MINE DRAINAGE

Bill Brown

Abstract: A wide range of environmental studies and mapping can be enhanced with helicopter and ground geophysical methods. While drill results can be definitive about the depth and type of stratigraphy, water content and subsurface contamination, they usually represent conditions at only one small location. Airborne geophysical data are less definitive, but cover a large area completely, mapping conductivity in three dimensions quickly and inexpensively. Once data are acquired, drilling can be targeted on the target zones picked from the geophysics, and only a few drill holes are needed to give some ground truth to the resistivity data. This allows a more accurate quantitative assessment of the target depth, thickness and total volume over the entire survey area. Fugro’s HEM data have been used as to assess sites, plan remediation and monitor the status of subsurface contamination.

Additional Key Words: resistivity, ground water, ARD, fracture zone, water table, conductivity

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GEOCHEMICAL PREDICTION AND REMEDIATION OPTIONS FOR THE PROPOSED MARTHA MINE PIT LAKE, NEW ZEALAND

Devin N. Castendyk and Jennifer G. Webster-Brown

Abstract. Upon closure in 2007, the Martha gold mine, New Zealand, will be flooded with river water creating a 192-m-deep pit lake. The mine owners intend to rehabilitate the lake into a public recreation area for boating and swimming, which will have additional value as a habitat for waterfowl and fish. This study demonstrates how a geochemical prediction of pit lake water quality can identify modifications to closure plans that will potentially improve post-mining water quality and increase the value of a proposed pit lake resource. The geochemical model PHREEQC was used to construct three, 55-year predictions of epilimnion and mixolimnion water quality in the proposed Martha pit lake, based on recent mineralogic and limnologic investigations. Model 1 considered the current closure strategy, whereas Model 2 covered all wall rocks that produced highly-acidic runoff (HAR) before lake filling (21 ha covered), and Model 3 covered only HAR rocks exposed above the steady-state lake surface (3 ha covered). After 50 years of steady-state conditions, Model 1 predicted that surface water will have a pH < 5.0 and will not comply with New Zealand water quality guidelines for recreational use. The epilimnion will also contain Cu and Zn concentrations that exceed aquatic life protection guidelines. By covering all HAR producing areas, Model 2 showed the epilimnion pH increased to 7.0 and Cu concentrations dropped significantly. Most significantly, Model 3 showed that covering only HAR producing areas exposed above final lake surface produced similar results to Model 2 after 50 years of steady-state conditions, increasing pH to 6.8 and lowering Cu concentrations. Zinc concentrations remained above aquatic life protection guidelines in each modeling scenario, and may limit the number of sensitive waterfowl and fish species utilizing the lake. Because only 11% of the wall rock area exposed above the steady-state lake surface will produce HAR, covering these wall rock areas is a feasible remediation option for the mine owners to consider, which is likely to improve future water quality and allow the pit lake to be used as a recreational resource.

Additional Key Words: modeling, PHREEQC, acid rock drainage

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HYDROGEOLOGICAL AND GEOCHEMICAL ASSESSMENT OF HISTORIC TAILINGS IN MINAS GERAIS, BRAZIL

Eduardo Chapadeiro\(^2\), Flávio Vasconcelos\(^2\), Celso Loureiro\(^3\), Irany Braga\(^4\)

**Abstract.** Hydrogeological and geochemical studies were conducted on historic tailings located along the Cardoso Creek near the municipality of Nova Lima, in the state of Minas Gerais, Brazil. These tailings, which contain elevated arsenic levels, date from the first half of the twentieth century and are currently owned by AngloGold Ashanti Ltd. The investigations had three principal components: a) environmental, hydrogeological and geochemical assessment, including monitoring wells installation, field and laboratory tests and dynamic modeling; b) preliminary risk analysis; and c) development of conceptual remediation solutions and management practices to prevent adverse impacts to human health and the environment.

**Additional Key Words:** arsenic, environmental risk, human health, groundwater, surface water

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\(^1\) Poster paper presented at the 7\(^{th}\) 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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HYDROGEOLOGY OF SOUTH BISON HILL

Denise Chapman², S.L. Barbour³, M.A. O’Kane⁴

Abstract. Oil sands mining in northern Alberta involve the stripping away of a saline-sodic overburden to gain access to the oil-bearing McMurray Formation. Once removed, the pyritic, saline, sodic, overburden is deposited into mined out pits or deposited as large surface fills. South Bison Hill is just one of these overburden structures. The long-term hydrogeologic system that develops within the South Bison Hill is unknown, both in terms of its final state and the time to reach this state. This newly developing groundwater flow system and its interaction with surface soils and water bodies with respect to water and salt fluxes must be defined. The primary objective of this study is to define the hydrogeologic features of South Bison Hill by documenting the hydraulic and geochemical factors controlling the evolution of the hydrogeologic system and then using these factors to develop an interpretative model of this system.

Additional Key Words: reclamation, piezometer, rising head test, groundwater flow model

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Abstract: Metals in mine effluents, especially metal mines, have been a major
environmental concern. High mobility of the metals in solution and the
subsequent lowering of discharge limits by the EPA have necessitated expensive
chemical treatment of the effluent. Bacteriological reactions, particularly by
Sulfate Reducing Bacteria, have been known to reduce metals content in water by
precipitating them as metal sulfides. The technique was used on samples of
untreated mine plant water (prior to treatment for disposal) from the Teck-
Cominco Red Dog Mine in northern Alaska. Further experiments were conducted
to determine bioreactor design parameters. Bioreactor lab tests revealed that
metal content was reduced by over a hundred fold. Pilot scale test cells were
established in the Red Dog mining area and their performance was monitored.
GEOCHEMICAL AND GEOTECHNICAL CHARACTERISTICS OF FILTER-PRESSED TAILINGS AT THE GREENS CREEK MINE, ADMIRALTY ISLAND, ALASKA

Peter D. Condon and Kerry G. Lear

Abstract. The Greens Creek Mine’s 3.5M tonne dry-stack tailings pile receives about 800 tonnes of filter-pressed tailings daily. The silt-sized tailings are placed in thin, compacted lifts using a bulldozer and vibratory roller. Carbonate minerals produce a long lag time to acid generation despite a net-neutralization potential of -210 tonnes CaCO3/ktonne.

Key influences on pore water compositions include near-surface pyrite and thiosulfate oxidation, vadose zone iron and manganese reduction and saturated zone sulfate reduction. Annual precipitation in excess of 1450 mm poses the largest challenge to achieving design placement densities in this seismically active region.

Despite higher operational costs relative to slurry-tailings disposal, the decision to produce dewatered tailings provided economic and environmental advantages. It reduced the ultimate footprint of the facility, lowered closure and water treatment costs, improved pile stability and reduced environmental liability by allowing half of the tailings to be returned underground for use as structural backfill.

Additional Key Words: thiosulfate, sulfate reduction, ARD, Proctor density, costs

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DEVELOPING A METHOD OF SITE QUALITY EVALUATION FOR QUERCUS ALBA AND LIRIODENDRON TULIPIFERA IN THE EASTERN KENTUCKY COALFIELDS

Claudia Cotton¹ and Christopher Barton²

Abstract. Kentucky is currently experiencing a shift in the revegetation of its reclaimed mine sites. Grasses and agronomic crops have been used previously for this purpose; however, reclamation through reforestation is becoming more common due to carbon sequestration, biomass fuel, and bond release issues. Historically, the evaluation of reforestation efforts on mined lands has come from regional site indices (based on 50-year old trees) and assessments of tree height and survival. Unfortunately, these methods fail to grasp the overall quality of the trees or site. With this in mind, a project is currently underway that will develop reference curves based on tree and soil variables measured on a chronosequence of sites for two species of trees: white oak (Quercus alba) and yellow poplar (Liriodendron tulipifera). For each species, eight even-aged stands will be identified and sampled throughout the Eastern Kentucky Coal Fields according to the following age classes: 5, 10, 20, 40, and 80. A total of 40 stands will be sampled per species. Using regresional relationships, we hope to project forward growth curves from the mine sites and compare them to those developed from the reference, or natural, sites to determine if they are on a similar trajectory. This method will not only evaluate tree survival, but will also determine whether or not the stand is comparable to a naturally regenerated stand on non-mined land. The evaluation of reforested mine sites is the catalyst for this study; however, the growth curves will serve an additional function by being a base reference for white oak and yellow poplar systems in Eastern Kentucky. Overall, we hope to develop a method of characterization that may be applied to any species in any region for multiple purposes.

Additional Key Words: site characterization, reforestation, reclamation, white oak, yellow poplar.

¹Poster 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

²Claudia Cotton, Research Assistant, Department of Forestry, University of Kentucky, 208 TP Cooper Building, Lexington, KY 40502. Christopher Barton, Assistant Professor, Forest Hydrology and Watershed Management, Department of Forestry, University of Kentucky, 203 TP Cooper Building, Lexington, KY 40502.
SUCCESSFULLY LOWERING THE RISKS AND COSTS ASSOCIATED WITH THE LEGACY OF THE ABANDONED BRUKUNGA PYRITe MINE, SOUTH AUSTRALIA1.

Ray Cox, Peter Grindley, Jeff Taylor and Sophie Pape2

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

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RELATIONS AMONG pH, SULFATE, AND METALS CONCENTRATIONS IN ANTHRACITE AND BITUMINOUS COAL-MINE DISCHARGES, PENNSYLVANIA

Charles A. Cravotta III

Abstract. Water-quality data for discharges from 140 abandoned mines in the Bituminous and Anthracite Coalfields of Pennsylvania illustrate relations among pH, sulfate, and dissolved metal concentrations. The pH for the 140 samples ranged from 2.7 to 7.3, with two modes at pH 2.5 to 4 (acidic) and 6 to 7 (near neutral). Generally, flow rates were smaller and solute concentrations were greater for low-pH samples; flow rates increased with pH. Although the pH distribution was similar for the bituminous and anthracite subsets, the bituminous discharges had smaller median flow rates, greater concentrations of sulfate, iron, and aluminum, and smaller concentrations of barium and lead than anthracite discharges with the same pH values. The observed relations between the pH and constituent concentrations can be attributed to (1) dilution of acidic water by alkaline ground water; (2) solubility control of aluminum, iron, manganese, barium, and lead by hydroxide, sulfate, and/or carbonate minerals; and (3) aqueous sulfate-complex formation. The formation of AlSO$_4^+$ and AIHSO$_4^{-2}$ complexes adds to the total dissolved aluminum concentration at pH of equilibrium with aluminum hydroxide or hydroxysulfate minerals and can account for 10 to 20 times greater concentrations of dissolved aluminum in bituminous discharges compared to anthracite discharges at similar pH. Sulfate complexation also can account for 10 to 30 times greater concentrations of dissolved ferric iron concentrations at equilibrium with ferrihydrite (Fe(OH)$_3$) and/or schwertmannite (Fe$_3$O$_4$(OH)$_{4.5}$(SO$_4$)$_{1.75}$) at pH of 3 to 5. In contrast, lower barium and lead concentrations in bituminous than anthracite discharges indicates elevated sulfate concentration could decrease mobility of these metals by the formation of insoluble minerals such as barite (BaSO$_4$) or anglesite (PbSO$_4$). Most samples were saturated with barite, but none were saturated with anglesite. Hence, lead concentrations could be controlled by coprecipitation with barite and/or by adsorption to schwertmannite or another sulfate-bearing oxide.

Additional Key Words: speciation, solubility, iron, aluminum, manganese, barium, lead.
PARAMETRIC STUDY ON THE WATER CONTENT PROFILES AND OXIDATION RATES IN NEARLY SATURATED TAILINGS ABOVE THE WATER TABLE

Anne-Marie Dagenais\textsuperscript{2}, Michel Aubertin, Bruno Bussière

Abstract. A promising concept, known as the elevated water table, is emerging as a management and possible closure technique to limit AMD production from tailings impoundments. This prevention approach is based on the principle that tailings in the capillary zone can be maintained in a state close to full saturation which minimizes oxygen diffusion and thus limits acid generation. A parametric study was conducted to evaluate the effect of various factors on the water content profiles in reactive tailings. The results presented here show that the position of the water table has a large influence on the water content profiles and on the oxygen flux at the tailings surface. For a water table depth value smaller or equal to the tailings’ air entry value ($\psi_a$), the degree of saturation $S_r$ varies between 90 to 99\% at the tailings surface, covered by a sand protection layer. These high $S_r$ values yield effective diffusion coefficient $D_e$ comparable to that of $O_2$ diffusion in water. The study also shows that the efficiency of the elevated water table concept can be negatively affected when the tailings are highly reactive.

Additional Key Words: elevated water table, modeling, water content profiles, oxygen flux, unsaturated conditions.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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FUNDING REQUIREMENTS FOR LONG-TERM POST-MINING DISCHARGE TREATMENT

T. P. Danehy, G. T. Hilton, C. F. Denholm, S. L. Busler, M. H. Dunn

Abstract: Recent changes in Pennsylvania require mining companies to post bonds or establish trust funds to cover costs associated with the perpetual treatment of post-mining discharges. Substantial cost savings can be realized by critically evaluating annual operation and maintenance costs and updating treatment systems. Several scenarios, including active and passive treatment technology, are evaluated to demonstrate the impact of capital, annual and recapitalization costs on funding requirements. Treatment and financial guarantee options can influence total out-of-pocket expenses for even a low-flow, moderately acidic discharge by about ½ million dollars.

Additional Key Words: Passive Treatment, Active Treatment, Liability, Cost Evaluation

1Poster 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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ASSESSMENT OF ARD EFFECTS ON RIVER ECOSYSTEM USING BENTHIC AQUATIC MACROINVERTEBRATES (MARINDUQUE ISLAND, PHILIPPINES)¹

Carlos Primo C. David²

Abstract. The benthic macroinvertebrate community in the Boac River (Marinduque Island) is controlled by the dissolved copper concentration from the acid rock drainage originating from the Marcopper Mine. A four-year survey shows how the benthic community composition responds to the prevailing Cu concentration in the water. The point of first macroinvertebrate occurrence, species richness, and metal bioaccumulation data all correlate well with Cu concentration. Continuing this biomonitoring protocol may be advantageous in terms of determining water quality trends and how remediation efforts in the Boac River may be assessed.

¹Poster 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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COMPARISON OF DISSOLVED COPPER CONCENTRATION TRENDS IN TWO RIVERS RECEIVING ARD FROM AN INACTIVE COPPER MINE (MARINDUQUE ISLAND, PHILIPPINES)\textsuperscript{1}

Carlos Primo C. David\textsuperscript{2} and Geoffrey S. Plumlee

Abstract. The Boac and Mogpog Rivers in Marinduque Island (Philippines) receive acid rock drainage from the inactive open-pit Marcopper Mine. Fairly similar dissolved Cu concentrations (20-25 mg/L) enter both rivers from the mine site. However, due to differences in size, hydrology and the acid neutralization ability of rocks between each watershed, the downstream geochemical impacts of the acid-rock drainage become markedly divergent. Dilution, interaction with waters and minerals having high acid-neutralizing capacity, precipitation, and particulate settling are the prevalent processes in the attenuation of dissolved Cu loads. Understanding the importance of each of these mechanisms will help in the selection and optimization of remediation efforts in the mine site to be able to achieve a minimum acceptable river water quality downstream.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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GEOCHEMICAL CONTROLS ON WASTE-ROCK DUMP SEEPAGE CHEMISTRY AT SEVERAL PORPHYRY MINES IN THE CANADIAN CORDILLERAN¹

Stephen Day and Ben Rees²

Abstract. In 2003, Red Chris Development Company started collecting baseline data to support its application for environmental approvals to mine the Red Chris porphyry copper-gold deposit located in northwestern British Columbia, Canada. An extensive geochemical testing program revealed that the majority of the waste rock has the potential to generate acid. However, the presence of significant quantities of carbonate minerals indicated that most of the rock would probably take several decades to generate acid. This precluded determination of which rock components would leach under acidic conditions using conventional laboratory methods. This information was required to predict future water chemistry and potential requirements for water treatment. As an alternative, waste-rock seepage chemistry data from six operating or recently closed porphyry mines in British Columbia were compiled and evaluated to investigate common hydrogeochemical features which could be used to predict water chemistry at Red Chris. The resulting database contains dissolved ion chemistry spanning the full range of pH conditions.

The database indicated that dissolution of aluminum minerals such as biotite and chlorite exert a strong consistent pH control which can be explained by the solubility of basic aluminum sulfates and hydroxide. Likewise, iron concentrations were similar at all sites and appear to follow the solubility of ferric hydroxide. Dissolved concentrations of copper, zinc, cadmium, and molybdenum in waters were related to pH but reflected the variable presence of minerals such as chalcopyrite, sphalerite (zinc, cadmium) and molybdenite (molybdenum). In conclusion, concentrations of major ions affecting drainage acidity (sulfate, aluminum, and iron) are very similar at different sites, but concentrations of other elements depend on the abundance of their sulfide minerals.

Additional Keywords: Acid rock drainage, prediction, metals.

¹Paper 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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PRECIPITATING IRON MINERALS AT LOW PH: A NEW CONSIDERATION IN PASSIVE TECHNOLOGY

C. F. Denholm², G. T. Hilton², T. P. Danehy², S. L. Busler², M. H. Dunn²

Abstract: Low-pH (≤3.5) drainage with dissolved ferrous and ferric iron is often unfeasible to treat with organic media due to required space, costs, and maintenance of passive components that remove iron solids at circumneutral pH. Precipitation of minerals at low pH, such as, jarosite [KFe₃(SO₄)₂(OH)₆] in solid solution with hydronium jarosite [(H₂O)Fe₃(SO₄)₂(OH)₆], not only decreases iron and sulfate in solution but also generates less acidity and sludge (by volume) when compared to amorphous solids formed at circumneutral pH. Components designed for alkalinity generation and settling of solids, to be installed after precipitation of these minerals, therefore, require less space and maintenance.

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²Clifford F. Denholm, Env. Sci.; G. Tiff Hilton, Mining Eng.; Timothy P. Danehy, QEP; Shaun L. Busler, GISP; Margaret H. Dunn, PG, CPG; BioMost, Inc., 3016 Unionville Rd., Cranberry Twp., PA 16066; 724-776-0161; 724-776-0166(fax); bmi@biomost.com
THE USE OF SYNTHETIC JAROSITE AS AN ANALOG FOR NATURAL JAROSITE

George A. Desborough, Kathleen S. Smith, Heather A. Lowers, Gregg A. Swayze, Jane M. Hammarstrom, Sharon F. Diehl, Rhonda L. Driscoll, and Reinhard W. Leinz

Abstract. The presence of jarosite in soil or mining waste is an indicator of acidic sulfate-rich conditions. Physical and chemical properties of synthetic jarosites are commonly used as analogs in laboratory studies to determine solubility and acid-generation of naturally occurring jarosites. In our work we have mineralogically and chemically characterized both natural and synthetic jarosites. Analysis of 32 natural hydrothermal and supergene K- and Na-jarosites indicates no (< 5 mole %) solid solution between K and Na end members. Instead, our detailed study of cell dimensions and composition reveals discrete mixtures of K and Na end members. Hydronium-bearing jarosite was detected in only one natural sample, and it appears that hydronium-bearing jarosites are metastable. Although the presence of hydronium in jarosite cannot be directly measured, we found that when synthetic hydronium-bearing jarosites are heated at 120°C for 78 days or 240°C for 24 hours, Fe(OH)SO₄ is formed. The Fe(OH)SO₄ is easily detected by X-ray diffraction and, hence, can be used as a post-mortem indicator of the presence of hydronium jarosite. Results from our synthetic jarosite studies indicate that natural metastable hydronium-bearing jarosite or iron-deficient forms of natural jarosite likely play an important role in acid generation in some mining wastes, but are not accurately represented by synthetic jarosite prepared by commonly used methods. The widespread practice of heating to at least 110°C after jarosite synthesis appears to drive off structural waters from protonated hydroxyl sites, which changes the properties of the jarosite. Therefore, synthetic jarosite should not be heated above 95°C if it is to be used as an analog for low-temperature natural jarosite in mining wastes.

Additional Key Words: mining waste, acid generation, hydronium jarosite, natrojarosite

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CEMENTED PASTE BACKFILL LEACHATE CHARACTERISTICS - SNAP LAKE DIAMOND MINE

Ken DeVos and Rens Verburg

Abstract. A geochemical study was completed as part of an Environmental Assessment Report for De Beers Canada Inc. Snap Lake diamond mine located in the Canadian Northwest Territories. The deposit will be mined using underground methods and consists of a diamond bearing planar kimberlite dyke dipping at about 15 degrees, hosted in metavolcanic and granite rock. Processing will include grinding of the kimberlite ore and a gravity separation circuit on this ore which will result in processed kimberlite waste including a coarse fraction and a finer fraction which will be used to produce a cemented paste backfill material. The cemented paste composed of processed kimberlite, dilution rock, and cement is thickened to a paste-like consistency and will be used to fill the mine voids.

The study discussed in this paper was completed to evaluate potential leachate chemistry of the alkaline cemented paste backfill material slated for use underground. The laboratory test program included solids testing, short-term leach testing, and longer-term kinetic testing on a variety of cemented paste blends and additives. Results show that the pH of the leachate remained alkaline for subaqueous test cells and decreased over time for sub-aerial test cells. Geochemical speciation modeling using PHREEQC that was completed to further evaluate leachate chemistry for site specific conditions indicated probable solubility constraints due to secondary mineral precipitation for parameters calcium, chromium, manganese and nickel.

Additional Key Words: kinetic, alkaline, PHREEQC, cement, paste, backfill, kimberlite.

1 Poster 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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MICROBIAL STUDY OF THE MARINE SHORE PORPHYRY COPPER TAILINGS DEPOSIT BAHIA DE ITE, PERU

Nouhou Diaby\textsuperscript{2*}, Bernhard Dold\textsuperscript{2}, Christof Holliger\textsuperscript{3}, Rodolfo Vicetti\textsuperscript{4}, Ezio Buselli\textsuperscript{4}

\textbf{Abstract.} Preliminary results of a microbiological study of the marine shore tailings disposal at the Bahia de Ite (tailings from Toquepala and Cuajone porphyry copper mines, Peru) are presented. The goal of the study is to understand the microbiological communities and its distribution in the tailings profiles before and after the installation of a wetland on the marine shore tailings deposit. The tailings have low sulfide (\textasciitilde 2 wt\% pyrite equivalent) and low carbonate contents. Molecular based methods, mainly terminal restriction fragment length polymorphism (T-RFLP), cloning and sequencing as well as cultivation methods were applied to characterize the microorganisms. Iron/sulfur oxidizing bacteria (e.g. \textit{Leptospirillum}, \textit{Acidithiobacillus} and \textit{Sulfobacillus}-like) and heterotrophs (e.g. \textit{Acidiphilium} and \textit{Acidobacterium}-like) were present in the still oxidizing tailings. The maximum bacteria, as determined by total cell count, were detected at the oxidation front where sulfide minerals as pyrite and oxygen are both available. These tailings are characterized by a low biomass and a low bacterial diversity. In the remediated zone, due to the less extreme condition, the bacterial diversity was higher and a dominance of heterotrophs and sulfate reducing bacteria (SRB) were expected in this zone.

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} 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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EFFECTS ON ELEMENT MOBILITY BY THE CONSTRUCTION OF A WETLAND ON THE MARINE SHORE PORPHYRY COPPER TAILINGS DEPOSIT, BAHÍA DE ITE, PERU¹.

Nouhou Diaby², Bernhard Dold²*, Ezio Buselli³, Rodolfo Vicetti³

Abstract. The marine shore tailings deposit at the Bahía de Ite, Atacama desert, Southern Peru was studied in order to understand the biogeochemical processes resulting from the construction of a wetland on the oxidizing tailings. For this purpose, un-remediated and remediated parts of the tailings were studied by solid and aqueous geochemistry, mineralogy, and microbiology methods. Preliminary results show that the oxidizing tailings have a low-pH oxidation zone (pH 1 – 4) with a strong accumulation of efflorescent salts (10 – 20 cm thick) at the surface due to the upward capillary transport of metal cations in the arid climate (up to 800 mg/L Fe, 160 mg/L Cu, 15 mg/L Zn, 70 mg/L Mn, 0.2 mg/L Cd, 1.3 mg/L Co and 2.5 mg/L Ni). In contrast, these bivalent metals occur in very low concentrations (mainly under the detection limit) below the wetland due to the established near neutral pH and reducing conditions (~150 mV). The alkaline waters (pH 8) that infiltrated into the Bahía de Ite tailings deposit contained high natural background arsenic concentrations (~500 µg/L As). The preliminary data suggest that the infiltration of the wetland induced retention of the metal cations and the formation of a Fe(II) plume. The Fe(II) plume was pushed toward the sea due to the increased hydraulic pressure of the wetland, where, in contact with the more oxidizing (400 mV) and alkaline sea water, the precipitation of Fe(III) hydroxides was triggered in the area of the shore line. In the shoreline samples, the As concentrations in the pore water are below the detection limit, suggesting that the As is retained by the Fe(III) hydroxide. This conclusion was confirmed by sequential extraction data.

Additional Key Words: acid mine drainage (AMD), efflorescent salts, wetlands remediation, pyrite oxidation, marine deposit.

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Abstract. Weathering is important in the development of rock fabrics that control porosity in mine-waste materials, and in turn, porosity affects metal transport through and from mine-waste piles into watersheds. Mine-waste piles are dynamic physical and chemical systems as evidenced by remnant Fe-oxide boxwork structures after sulfide minerals, development of alteration rinds and etch pits on grains, and precipitation of secondary minerals under low temperature conditions. These microscale changes in the mine-waste materials are the result of partial to total dissolution of sulfide and other minerals.

Mine-waste materials from the Dinero, Lower Chatauqua, and Saints John sites, Leadville and Montezuma mining districts, Colorado, exhibit rock fabrics that indicate that weathering products, e.g., Fe oxyhydroxides, jarosite, and clays, have been transported in suspension through the waste piles and deposited in voids and as coatings on rock fragments. Microscale characterization of weathered, partially dissolved minerals lends insight into the source of leachable metals in these mine-waste sites. Mineralogic studies show that galena in the Lower Chatauqua waste is enriched in Ag. Qualitative and semiquantitative microanalysis of weathered, altered galena grains from all three sites show that the Ag-bearing galena is more susceptible to dissolution. It is not surprising, then, that solutions experimentally leached from Lower Chatauqua waste are higher in Pb (2310 ppb) compared to leachates from the Dinero (31 ppb) and Saints John (1360 ppb) wastes.

The mobility of metals is increased at acidic pH. Using the USGS Field Leach Test protocol, leachate derived from the Dinero waste has a pH of 3 and high concentrations of Al (443 ppb), Fe (441 ppb), and Zn (7970 ppb). Leachate from Sts. John tailings has a pH about 4 and high concentrations of Mn (1520 ppb), Zn (2240 ppb), and Pb (1360 ppb). Leachate from the Lower Chatauqua waste has an intermediate pH of 5, but in addition to the high Pb level already mentioned, it contains high levels of K (1.9 ppm), Mn (6720 ppb), and Zn (1550 ppb). The high concentration of metals, despite the intermediate pH of the leachate, may be explained by acidic microenvironments that exist at the surfaces of sulfide minerals, where sulfur- and iron-oxidizing microbes may flourish. It is at the reactive mineral-oxygen-water interface where metals are released and low-pH sulfate precipitates such as jarosite-beudantite form.

Additional Key Words: dissolution, jarosite, anglesite, microlamination, leachate
MEASUREMENT OF MOISTURE CONDITIONS FOR MINE WASTE STORAGE FACILITIES USING THE DEEP DIVINER MOISTURE PROBE

Bonnie Dobchuk, S. Lee Barbour, Jeff Dobchuk and Mike O’Kane

Abstract. There is a need to measure deep in situ moisture conditions for all types of waste storage facilities in a safe, cost effective, practical, and efficient manner. This paper describes the Deep Diviner moisture probe, a deep capacitance moisture sensor, which has been developed by the authors with the assistance of the Canada Industrial Research Assistance Program (IRAP). The deep capacitance moisture probe uses the Diviner 2000® , a portable capacitance soil moisture monitoring sensor manufactured by Sentek Sensor Technologies. This portable probe was developed for irrigation management, and is a non-radioactive sensor. Development of the deep capacitance moisture probe involved modifying the Diviner 2000®, which has a limited depth range of 1.6 m, to allow the measurement of volumetric water content to depths of 40 m or 50 m, and possibly deeper. A winch / cable assembly was developed to lower the sensor down within a PVC access tube to allow for fully automated measurement of in situ moisture contents at user specified depth intervals, each of which are recorded on a portable datalogger. The prototype of the deep capacitance moisture probe was tested both in the laboratory and in a full-scale field situation to ensure the required hardware modifications were functional. Full scale field testing was also completed on the prototype. The results of this testing show that the deep capacitance moisture sensor is capable of measuring the water content of till and sand materials to depths of 6 m. This paper describes the development and testing of the deep capacitance moisture.

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HYDRAULIC PLACEMENT OF A DRY COVER SYSTEM - DESIGN AND PERFORMANCE MONITORING OF THE KENNECOTT RIDGEWAY MINE TAILINGS DAM COVER SYSTEM

R. Duckett and M. O’Kane

Abstract. The Kennecott Ridgeway Mining Company (KRMC) tailings facility was built using run of mine waste and downstream embankment construction techniques. Approximately 60% of the 60 million tons of processed tailings have a negative net neutralization potential. KRMC conducted a cost-benefit analysis supported by a detailed cover system design and determined that a hydraulically placed cover system was the preferred closure option for the tailings facility. The tailings mass (124 ha, or 307 acres) was covered with 2.7 million tons of clay material (saprolite) using hydraulic placement from both centre-point and ring discharge points following cessation of operations in November 1999. Approximately 90% of the tailings surface area is now covered with greater than 90 cm (36 inches) of cover material.

Monitoring was initiated in September 2001 to evaluate the field performance of the tailings dam cover system. Three primary tailings monitoring sites were established to provide continuous measurements of in situ suction, moisture content, and temperature conditions. Sixteen secondary tailings monitoring sites were also installed. The secondary monitoring sites provide spatial coverage to evaluate cover system performance. Surface runoff across the cover surface during precipitation events is also monitored.

This paper summarizes the design and implementation of the hydraulically placed KRMC tailings dam cover system. The cost benefit of implementing this novel cover placement technique is discussed. The field performance monitoring system is described and field data is discussed and summarized in light of the cover system design objectives for minimizing oxygen ingress.

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SUSTAINABLE MINING BEST PRACTICES AND CERTIFICATION

Drummond “Dusty” Earley III and Margaret “Poppy” W. Staub

Abstract. Sustainable mining concepts are being applied to current mining practices; however, assessment tools or criterion for best available mining and reclamation practices are needed. Environmental regulations and market incentives must align with these assessment tools before enhanced environmental performance and sustainable mining practices can be realized. This paper uses an environmental management system methodology to evaluate the sustainability of pollution prevention practices, such as in-situ mining and mineral processing circuits that produce desulfured tails, and ameliorative practices that employ mine waste covers and reclamation. This paper also discusses the conflict between the current regulatory process and the need for more innovative mining practices.
SIMULATIONS OF THE NEUTRALIZING CAPACITY OF SILICATE ROCKS IN ACID MINE DRAINAGE ENVIRONMENTS

L. Edmond Eary and Mark A. Williamson

Abstract. Pyritic rocks with little or no carbonate mineral content generally produce acid mine drainage when exposed to the atmosphere and moisture. In the absence of carbonate minerals, it is often suggested that silicate minerals can provide some level of acid buffering. At the current time, databases of reaction kinetics are sufficiently detailed to allow calculations of the rates of silicate mineral dissolution reactions relative to the rate of pyrite oxidation. These types of calculations have been conducted for conditions of abiotic oxidation of pyrite by O₂ to estimate the acid neutralizing capacity of silicate rock types in terms of specific mineral contents. Using the criteria of maintaining a pH > 5.0 for 10-years, these calculations yield the following results for some generalized igneous rock types.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>NP Range (kg CaCO₃/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>0.6</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Monzonite</td>
<td>2.0-2.7</td>
</tr>
<tr>
<td>Monzonite</td>
<td>2.2-3.0</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>1.8-2.2</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Diorite</td>
<td>18.9-29.2</td>
</tr>
<tr>
<td>Diorite</td>
<td>26.7-40.2</td>
</tr>
<tr>
<td>Gabbro</td>
<td>29.2-50.1</td>
</tr>
</tbody>
</table>

The results show that it is feasible to use geochemical model calculations to estimate neutralization potentials through reaction rate calculations, although these calculations tend to overestimate neutralization potentials of mafic rock types compared to experimental data. The rate calculations also point out the importance of the mafic mineral content for neutralizing acidity in that minerals, such as calcic plagioclase, forsterite, augite, and hornblende, may react rapidly enough to keep up with the rate of acid generation by pyrite oxidation under the right circumstances, whereas the felsic minerals, such as K-feldspar and albite, react too slowly to mitigate acid generation. The calculations also show the importance of secondary mineral formation in estimating neutralization potential in that equilibrium with goethite and gibbsite yields the low end of the range listed in the above table relative to equilibrium with amorphous Fe and Al hydroxides. Overall, the kinetics simulation procedures provide an efficient and inexpensive means to conduct scoping studies of likely pH conditions for carbonate-poor rocks that can be used to optimize sample selection for more detailed experimental testing or prediction of potential impacts from acid mine drainage based on petrological and mineralogical data in the absence of detailed experimental data.

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THE USE OF MICROENCAPSULATION TO PREVENT ACID ROCK DRAINAGE

Paul Eger² Paul Mitchell³

Abstract: Two commercially available microencapsulation products were tested for their ability to coat unoxidized pyrite and prevent its oxidation. EcoBond-ARD™, a phosphate based compound and KEECO KB-SEA™, a silica based product, were each applied to an unoxidized acid generating waste rock. Three application rates were selected by each company and represented a low, optimum and high application. Laboratory testing has been conducted in humidity cells for 168 weeks.

Cells with untreated waste rock (controls) produced drainage below pH 6.0 after 1 week and had an average pH of about 3.3 after 60 weeks. EcoBond-ARD™ delayed the onset of acidification but it was not successful in preventing acid drainage. The pH in all cells treated with EcoBond-ARD™ decreased to below 6 after 12-16 weeks. These cells were terminated after 59 weeks when the pH had decreased to around 3.5, essentially the same as in the controls. Possible explanations for the failure of the EcoBond-ARD™ included insufficient contact time to oxidize the surface of the pyrite or the absence of a durable coating. Additional concerns with the EcoBond-ARD™ were elevated levels of phosphorus and arsenic in the drainage. Initial arsenic concentrations ranged from 400 to 800 µg/L, well above the newly proposed federal drinking water standard of 10 µg/L. Initial phosphate concentrations were 1300 to 3900 mg/L and water of this quality could cause algal blooms in downstream receiving waters. Concentrations did not decrease to below the concern level of 0.03 mg/L until about 30 weeks.

KB-SEA™ was successful in preventing acid drainage at all levels of treatment. However, the pH from all cells treated with this product was initially around 12. Although pH has decreased in all cells, the cells treated with 5% had pH values consistently above 9 for about 75 weeks. The rate of sulfide oxidation in these cells was about 10% of the rate measured in the untreated controls and visually there was little sulfide oxidation in the cells treated with the optimum and high application rates (3%, 5%). The pH in the low application rate reactors (1%) has declined slowly and was below 6.5 at 168 weeks. Some oxidation is visible in the reactors and the sulfate release rates had increased slightly.

¹Poster 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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SPATIAL AND TEMPORAL WATER CHEMISTRY VARIATIONS IN ACID ROCK DRAINAGE FROM THE TAILINGS AT THE RUTTAN MINE, LEAF RAPIDS, MANITOBA, CANADA. ¹

D. Jared Etcheverry, Barbara L. Sherriff, and Nickolay V. Sidenko²

Abstract: From 1973 until 2002, the Ruttan Mine extracted Cu and Zn ore from volcaniclastic and siliciclastic sequences of the Rusty Lake Greenstone Belt. Floatation refinement of the ore produced over 30 million tons of fine-grained sulfide tailings which were submerged in retention ponds. Since mine closure, through the addition of trenches and dyke cuts, there has been a systematic dewatering of the tailings ponds to prevent possible dyke collapse. Currently, the tailings are draining into the open pit and underground mine via Ruttan Lake. The purpose of this study is to understand processes and variability within aqueous media of the tailings, using geochemical, mineralogical and hydrogeological techniques.

Groundwater collected from monitoring wells installed within the tailings are at near neutral pH (6.0 – 8.2) with low concentrations of metals (Total Fe: <0.01 – 3.66 ppm; Al: <0.01- 0.29 ppm; Zn: <0.1 – 1.26 ppm; Cu: <0.05; and Sulfate 1522 – 3019 ppm). On-site rising head tests give an average hydraulic conductivity of the tailings of 4.8x10⁻⁵ cm/s. Geotechnical laboratory measurements gave average porosity and average grain size diameters of approximately 42 % and 0.05 mm, respectively. Tailings surface waters collected from pools and the trench streams are characterized by low pH (2.6 – 3.3) and high dissolved metal concentrations (Total Fe: 162 – 2526 ppm; Al: 17 – 500 ppm; Zn: 15 - 420 ppm; Cu: 0.5 – 27 ppm; and Sulfate 1650 - 3190). While tailings are exposed to the atmosphere the breakdowns of sulfides by oxidation processes releases metals and sulfate and adds H⁺ ions into solution. The precipitation of jarosite and schwertmannite (from XRD analyses) from surface water does not change concentrations of the metals in the water because of the limited sorption of cations to these minerals at low pH.

Differences between tailings surface- and ground-water chemistry suggests that groundwater is not impacted by surface process. The paucity of pH buffering minerals within the tailings implies that some other process is involved in either buffering the groundwater or acting as a barrier between the two to produce the neutral pH condition within the tailings groundwater. Sequential extraction and porewater analyses of the tailings will help pinpoint the location of heavy metals at various depths within the tailings which may help determine the processes involved in creating the difference between surface- and ground-water.

¹Poster 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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NEUTRALIZATION OF ACID ROCK DRAINAGE USING A FLUIDIZED LIMESTONE REACTOR

Louis Evans, Ros Green, David Scott, and Jason Milne

Abstract. A cost effective treatment system for acid rock drainage using a cone shaped Fluidised Limestone Reactor (FLR) has been extensively investigated by both field and laboratory tests. A pilot scale system (with a flow rate of 100 Lpm and treatment of 130 mg/L CaCO₃ acidity) has been used in a mine lake system, successfully achieving suitable water quality for an aquaculture facility. This system was designed based on investigations into fluidisation dynamics, armouring, particle sizes and chemistry.

The reactor comprises a cone shaped container of limestone in which water is pumped through the limestone from the base of the cone. The water pressure causes the limestone to fluidize, thereby maximizing the contact between the limestone particles and the acid water and avoiding channeling effects that occur in static limestone treatment systems. One of the attractive features of the fluidized limestone reactor is its ability to minimize armourisation of limestone particles during the dissolution process. This is primarily achieved through the abrasion action induced by the agitation caused by the water flow. Armoring is avoided in the FLR by virtue of the container design, and also by controlling the pH in the effluent water so it does not exceed pH 6.0.

Control of pH remediation in the FLR is achieved by ensuring that the shape of the container is specifically designed for: 1) the desired input flow rate; 2) the limestone proposed for use in the reactor; and 3) the pH of the influent water. Design parameters for the purpose-built cone reactor are derived by conducting tests at the proposed installation site using the influent water and the limestone proposed for use in the full scale treatment system.

The fluidized limestone reactor will be most cost effective if it is incorporated into a passive treatment system with the reactor taking the pH from pH 3 to pH 4-5 linked to either wetlands or a carbon reactor that takes the pH from pH 4-5 to pH 6 and removes metal contaminants. After both treatments the water is suitable for agriculture/horticulture/aquaculture uses or for simply releasing into the receiving environment.

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NUMERICAL SIMULATIONS OF LONG TERM UNSATURATED FLOW
AND ACID MINE DRAINAGE AT WASTE ROCK PILES

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**Abstract.** The authors present a numerical modeling study of unsaturated water flow and acid mine drainage in idealized (but representative) waste rock piles and using observed climatic recharge data. The simulations were used to help understand the long term hydrogeological behaviour and to help design and assess in situ groundwater monitoring methods. The flow simulations showed that when the same annual cycles of average monthly recharge are applied each year at the top of the piles, the water content profiles become periodic after a few years. The water distribution within the piles then becomes independent of the preceding hydraulic conditions for the cases considered here. Also, the results indicate that the amplitude of water content variations inside the pile between humid and relatively dry seasons is generally small (a few percent). Consequently, typical measurements of the water content variations can, in some cases, be limited for in situ monitoring because their level of precision is often of same order of magnitude as the expected changes. Long term simulations of oxygen diffusion and acid mine drainage through the waste rock piles showed that oxygen is generally not a limiting factor in the unsaturated zones of these types of systems and that preferential flow, moisture content and grain size can have a significant influence on oxidation rates and pH distribution.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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RECLAMING THE COPPER BASIN OF TENNESSEE ¹

Ben B. Faulkner,² Franklin K. Miller, Franklin D. Russell

Abstract. For more than 150 years, the Copper Basin in Tennessee was the site of copper mining and acid production. It is one of the most dramatically impacted mining areas in the US. As part of voluntary remediation efforts, Glenn Springs Holdings has committed to actions with long-range goals of restoring biodiversity and biointegrity. This work follows decades of land reclamation and reforestation efforts on the 9,000 hectare site. Included are chemical treatment of acidic surface and underground mine drainage, land reclamation, passive treatment systems, restored streams, tailings and mine waste reclamation, waste characterization and pit disposal, pit limnology and leak studies, lead cap, hazards fencing, subsidence monitoring, stream diversion, bioassessment, and land use planning.

Additional Key Words: Ducktown TN, acid mine drainage, Ocoee River

¹Poster 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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PROPOSAL FOR AN INNOVATIVE APPROACH TO PREVENT ACID DRAINAGE FROM URANIUM MILL TAILINGS BASED ON THE APPLICATION OF NA-FERRATE (IRON VI)\textsuperscript{1}

Horst M. Fernandes\textsuperscript{2,3}, Debra Reinhart\textsuperscript{2}, Virender Sharma\textsuperscript{4}, Lucia Lettie\textsuperscript{3}, Mariza R. Franklin\textsuperscript{2,3} and Luke J. Daly\textsuperscript{5}

Abstract  The operation of uranium mining and milling plants gives rise to huge amounts of wastes from both mining and milling operations. Terrestrial deposition is the predominant method of disposal for waste-rock and tailings. When pyrite is present in these materials, the generation of acid drainage can take place and result in the contamination of underground and surface waters through the leaching of heavy metals and radionuclides. Ferrate (VI) is a powerful oxidizing agent in aqueous media. Under acidic conditions, the redox potential of the Ferrate (VI) ion is the highest of any other oxidant used in wastewater treatment processes. The standard half-cell reduction potential of ferrate (VI) has been determined as +2.20 V to +0.72 V in acidic and basic solutions, respectively. Despite numerous beneficial properties in environmental applications, ferrate (VI) has remained commercially unavailable. Producing the dry, stabilized ferrate (VI) product required numerous process steps which led to excessive synthesis costs (over $20/lb) thereby preventing bulk industrial use. Recently a novel synthesis method for the production of a liquid ferrate (VI) based on hypochlorite oxidation of ferric ion in strongly alkaline solutions has been discovered (USPTO 6,790,428; September 14, 2004). This on-site synthesis process dramatically reduces manufacturing cost for the production of ferrate (VI) by utilizing common commodity feedstocks. This breakthrough means that for the first time ferrate (VI) can be an economical alternative to treating acid mining drainage generating materials. The objective of the present study was to investigate a methodology of preventing the generation of acid drainage by applying ferrate (VI) to acid generating materials prior to the disposal in impoundments or piles. Oxidizing the pyritic material in mining waste could diminish the potential for acid generation and its related environmental risks and long-term costs at disposal sites. Preliminary results presented in this paper show that the oxidation of pyrite by ferrate has half-life of about six hours. The stability of Fe(VI) in water solutions will not influence the reaction rate in a significant manner. New low-cost production methods for making liquid ferrate on-site makes this technology a very attractive option to mitigate one of the most pressing environmental problems in the mining industry.

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502
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PRELIMINARY RESULTS OF THE WATER FLOW MODELING IN AN ACID DRAINAGE GENERATING WASTE ROCK PILE LOCATED AT THE URANIUM MINING SITE OF POÇOS DE CALDAS – BRAZIL

Mariza Franklin$^{2,3}$, Horst Fernandes$^{2,3}$, George Yeh$^3$ and José Paulo S. de Azevedo$^4$

Abstract: The first uranium production center in Brazil began operation in 1982. After 13 years of a non-continuous operation, the mining activities were suspended definitively. Uranium was extracted by open pit mining. Operations gave rise to approximately $12.4 \times 10^6$ m$^3$ of waste rock, while the mill process generated a volume of approximately $2.39 \times 10^6$ m$^3$ of tailings. Regardless the fact that some studies developed in this area exist, a well defined plan of action, aimed at the remediation and rehabilitation of the site, has not been implemented yet. The main sources of pollutants to the environment are the tailings dam, the waste rock piles and the open pit. Pyrite oxidation was found to be the driving force in the leaching of metal and radionuclides into environment. It was estimated that acid drainage generation will last for 600 and 200 years from the waste rock and tailings respectively. Accurate prediction of the release rate of metal and radionuclides from these sources and their transport in the subsurface is a critical factor to the assessment of environmental impact and to the development of effective remediation strategies. In prevailing practice, the source term is evaluated using the dissolution rate of waste form and the solubility of radionuclides. The fate of pollutants is addressed by the use of Kd-based “reactive” transport models. This standard practice has obvious shortcomings, mainly because it can not produce a realistic representation of the system under study. The alternative to overcome these shortages is using more sophisticate models that could represent real complex problems. Reactive transport codes are powerful tools in the evaluation of coupled thermal–hydrological–chemical processes and in the prediction of the long-term performance of remediation strategies. The difference between the predictions from these two approaches can be as high as several orders of magnitude. Generally, conventional approaches produce predicted values higher than the measured ones. On the other hand, the use of reactive transport model requires a good knowledge of the simulated hydrogeochemical system, along with the choice of appropriated algorithms that can represent the most important processes.

$^1$Poster 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
LINKING THE WORLD TO ELIMINATE ACID ROCK DRAINAGE¹

Ross Gallinger² and Anne-Marie Fleury

Abstract. Acid drainage continues to be one of the most serious and potentially enduring environmental problems for the mining industry. The International Network for Acid Prevention (INAP) is an industry group actively seeking to eliminate the liabilities associated with acid drainage through networking, sharing information and research. Recognizing that regional groups with acid drainage programs would benefit from a global dialogue and sharing of information, INAP facilitated the creation of the Global ARD Alliance, composed of MEND (Mine Environment Neutral Drainage Program), ADTI (Acid Drainage Technology Initiative), ACMER (Australian Centre for Minerals Extension and Research) and PADRE (Partnership for Acid Drainage Remediation in Europe), covering Canada, United States, Australia and Europe.

This paper will explore the activities of INAP in advancing a global agenda of networking, sharing information and research to aid in our understanding and path towards eliminating the liabilities associated with ARD.

Additional Key Words: Global Alliance, technology transfer, networking, research

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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**GEOCHEMISTRY AND HYDROGEOLOGY OF ACID MINE DRAINAGE IN THE GREAT FALLS-LEWISTOWN COAL FIELD, MONTANA**\(^1\)

Christopher H. Gammons\(^2\), Terence E. Duaime, William S. Botsford, Stephen R. Parker, Tracy Grant

**Abstract.** The Great Falls–Lewistown Coal Field (GFLCF) in central Montana contains over 400 abandoned underground coal mines, many of which are discharging acidic mine water with serious environmental consequences. Completely submerged areas of the mines are not strongly acidic, whereas water quality quickly deteriorates in portions that are only partially flooded. In general, the pH of the GFLCF mine waters can decrease or increase after discharging to the surface, depending on the initial ratio of acidity, mainly as dissolved ferrous iron, to alkalinity, mainly as bicarbonate ion. Although the chemistry of many of the adit discharges is nearly constant with time, large diurnal and seasonal changes in the quality of down-gradient waters have been observed. Decreases in concentrations of dissolved Fe and Zn during the day at one location are explained by an increase in the rate of Fe\(^{2+}\) oxidation and precipitation of ferric hydroxide as the water warms. The precipitation of ferric hydroxide resulted in sorption of Zn\(^{2+}\), a reaction that was also thermodynamically favored by an increase in water temperature and pH during the afternoon. Historical efforts to passively treat acid mine drainage in the GFLCF using wetlands, limestone channels, and anoxic drains have been unsuccessful, due to the harsh climate, high metal concentrations, and acidity loads of the mine waters. Alternative mitigation concepts are currently being evaluated that focus on source control rather than treatment.

**Additional Key Words:** diel, diurnal, iron, zinc

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\(^1\)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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ACID PRODUCTION FROM THE LEACHING OF PYRITE AND CHALCOPYRITE

Andrea R. Gerson and Joan E. Thomas

Abstract. Pyrite and chalcopyrite samples were subjected to wet and dry cycles to mimic natural weathering. Eh and pH were measured directly after drainage. The pH (<2.5) of the effluent from the pyrite was consistent with predicted solution speciation. The oxidation rate of solution sulfide containing species is dependent on the solution Fe concentration. We propose that the pyrite effluent was at equilibrium at the time of Eh measurement whereas the chalcopyrite effluent was not. In the latter case the low solution concentration of Fe, due to precipitation results in the slow oxidation of the solution S species. Hence the pH of the chalcopyrite effluent (>5) is considerably higher than predicted on the basis of the measured Eh and solution S assay.

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THE ABANDONED MINE OPENINGS MAPPING ON COAL MINING RECLAMATION PROGRAM OF THE SANTA CATARINA STATE-BRAZIL

Cleber JoseBaldoni Gomes, Roberto Romano Neto, Antonio Silvio Jornada Krebs, Jose Eduardo Amaral, Lindomar Santos, and Tiago Meis Amboni

Abstract. The abandoned mine openings (AMO) mapping project has a goal to locate a number estimated of 1000 coal mine openings. Within an experimental area 173 abandoned openings were mapped, surrounding the city of Criciuma, in southern portion of Santa Catarina State in Brazil. A total of 18 of these openings discharge, in average, 1,334 m³/hour of acid mine drainage (AMD) that flows to watersheds carrying high level of metals, acidity and sulfates. A model of underground water flow was established through structural geology, and a digital terrain model (DTM) from the surface and mine floor, aiming to identify openings that collect surface water, and openings that discharge AMD. Openings started to be closed according to risks to safety, health and the environment. A monitoring program has been established since 2002 to quantify physical and chemical characteristics, and flow rates from discharges. A pilot water treatment plant was being installed near a portal (SS16), with the purpose to define treatment procedures and costs, aiming to use this treated water to supply the nearby community.

Additional Key Words: mapping, coal mine openings, AMD treatment.

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MINE WATER MANAGEMENT AT THE CATCHMENT SCALE: CASE STUDIES FROM NORTH-EAST ENGLAND

Emma Gozzard\textsuperscript{2}, William M. Mayes, Michelle I. Morrison and Adam P. Jarvis

\textbf{Abstract}. Recent implementation of the EU Water Framework Directive necessitates addressing water quality issues at the catchment scale. In this study, contaminant loading of all point discharges have been measured, establishing the overall impact of mine waters within the catchments, and allowing the derivation of contributions of diffuse mine water pollution to these totals. The results of two ongoing case studies of mine-impacted river catchments in the north-east of England are presented. The Allen catchment, Northumberland, is impacted by discharges from abandoned Pb/Zn mines with up to 6 mg/l Zn and 0.2 mg/l Pb, which significantly exceed European ecotoxicological standards by up to a factor of 75 and 20 respectively. The Gaunless catchment, County Durham, receives uncontrolled discharges of coal mine waters with up to 8 mg/l Fe. Preliminary findings show that during both low and high flow conditions diffuse iron pollution contributes significantly to in-stream iron loadings. Probable pathways include direct groundwater input and remobilisation due to scouring of streambed sediments.

\textbf{Additional Key Words}: diffuse sources, point sources, Water Framework Directive

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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Abstract. Nickel and uranium loadings from oxidized sulphide-bearing waste rock have been estimated at three successive scales: laboratory columns, a 320 m³-constructed pile (CPE) and the Claude waste rock pile. The Claude waste rock pile is approximately 20 years old and is composed of waste rock from the Claude open pit, which was mined for uranium on the Cluff Lake site, Northern Saskatchewan, Canada. The Claude waste rock pile is about 29 m high at its highest point and covers an area of 29.5 ha. It contains roughly 7.9 million tonnes of waste rock. Operational groundwater monitoring has been in place in the Claude pile area since 1991 with monthly hydraulic head and groundwater chemistry measurements. An assessment of the existing contaminant plume suggests that between 12% and 30% of the nickel and uranium inventory has been released to the groundwater system since initial construction of the pile. Based on sequential leach tests and unsaturated column leach tests results, these leached masses range from 25% and 45% of the total leachable mass for uranium and from 31% to 58% of the total leachable mass for nickel. This metal load was estimated be released during the first pore volume replacement of the waste rock pile. Field loading estimates for the CPE also suggested that a significant portion of the uranium and nickel mass was released during the first pore volume replacement of the waste rock mass, with calculated leached fractions on the order of 80% and 24% for uranium and nickel, respectively. For both the Claude waste rock and the waste rock used to construct the CPE, it is suspected that these high leached fractions are the result of a large quantity of readily soluble products that the waste rock has accumulated from a rapid weathering and oxidation of the sulphides. Subsequently, this suggests that the cover of the Claude pile should target an efficient reduction of infiltration rather than a reduction of oxygen ingress within the pile.

Additional Key Words: acid rock drainage, geochemistry, flow, contaminant transport.

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CONCEPTUAL METHODS FOR RECOVERING METAL RESOURCES FROM PASSIVE TREATMENT SYSTEMS

James J. Gusek, Thomas R. Wildeman, Kevin W. Conroy

Abstract. Recovering mineral resources retained in passive systems for treating acid drainage may be a way for mining companies to achieve sustainability goals. While the development of metallurgical methods for Fe oxide recovery from passive systems is underway, no parallel research effort has apparently been undertaken for the recovery of precious metals, sulfides, or carbonates from sulfate reducing bioreactors (SRBRs), another effective passive treatment technique. The examination of conceptual beneficiation, pyrometallurgical, and hydrometallurgical processes that might be used in resource recovery is a logical first step in this effort. Resource recovery process challenges include dealing with the abundance of organic matter in the SRBR substrate media and the dispersed and probably microscopic character of the metal precipitates.

Screening, wet classification, and roasting of the SRBR media appear to be common threads for recovering the four elements considered in the paper: copper, gold, silver, and uranium. As the SRBR technology matures further, research could help close the loop in a process that is now considered to be solely treatment.

Additional Keywords: sustainability, recycling, metals, beneficial uses, sulfate reducing bioreactors
APPLICATIONS OF A GLOBAL MINERAL-RESOURCE ASSESSMENT FOR ADDRESSING ISSUES OF SUSTAINABLE MINERAL RESOURCE DEVELOPMENT

Jane M. Hammarstrom, Joseph A. Briskey, Klaus J. Schulz, Stephen G. Peters, and Walter J. Bawiec

Abstract. The future of mining depends on balancing global demands for minerals with societal demands for sustainable development. The U.S. Geological Survey, in collaboration with a variety of international cooperators, is assessing the undiscovered global resources of copper, platinum-group elements, and potash at a scale of 1:1,000,000. Assessment products include maps that show significant identified deposits and permissive areas for undiscovered deposits, as well as probabilistic estimates of contained metal. Derivative products applicable to sustainability issues include maps showing the spatial relationship of permissive areas to infrastructure development, protected areas, threatened ecosystems, seismically active areas, and watersheds.

Additional Key Words: assessment, mineral resources, sustainability

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EVALUATING FOREST PRODUCTIVITY ON RECLAIMED MINE LAND IN THE WESTERN UNITED STATES

John T. Harrington and Mark W. Loveall

Abstract: Establishing forests as a post-mining land use has not been widely used in the western United States for a number of reasons. Most mine revegetation efforts in the western United States prior to the 1990’s focused on establishing either herbaceous or shrub communities because most existing reclamation expertise was associated with establishing these non-forest plant communities. Hence, few existing performance standards were designed for forested plant communities. Numerous investigations in the eastern United States have examined the use of site index to evaluate post-mined land forest productivity. This study reports preliminary results comparing early (less than 20-year) estimates of site index on a high elevation mine site to the performance of artificial reforestation on adjacent forested sites with known site indices in the western United States. Using incremental height analysis, ponderosa pine seedlings planted at two locations on a high elevation mine site were tracked for up to 20 years. Similarly, seedlings planted up to 19 years before the present time were also tracked on nine “undisturbed” forested sites with a range of site indices. No difference in the growth of seedlings through nine years was found between forest sites with high and low site indices. Ponderosa pine seedlings planted on mine overburden took 2 - 4 years longer to have appreciable height growth compared with seedlings on forested sites. However, once appreciable shoot growth had begun, seedlings planted on mine overburden demonstrated growth rates comparable to those planted on less disturbed sites (through 19 years).

Additional Key Words: reforestation, mined land reclamation, site productivity, transplant shock
HYPERSPECTRAL SENSING OF ACID MINE DRAINAGE –
TWO COLORADO CASE STUDIES

Phoebe L. Hauff, Douglas C. Peters, David W. Coulter, Matthew A. Sares, David A. Bird,
Frederick B. Henderson III, and Eric C. Prosh

Abstract. The upper Arkansas River basin of central Colorado contains
watersheds that are affected by acid rock drainage (ARD) from both natural and
mining induced sources, including the Leadville mining district. Hyperspectral,
high-resolution remote sensing technology is being used to characterize and map
the source mineralogy of ARD, changes in downstream water quality, and the
fluvial deposition of mine tailings downstream.

Two case studies are presented. The Lake Creek watershed is affected by
natural ARD, emanating from two sources which are sub-economic, sulfide-
mineralized, porphyry systems in the headwaters of two tributaries. Extreme
metal- and acid-loadings from source areas affect the watershed for 30 km
downstream. The main channel of the Arkansas River, primarily downstream of
the Leadville District, contains disseminated tailings distributed by fluvial
processes. The tailings are a continuing source of metals loading to the river.

The two watershed systems share common mineral coatings, such as jarosite
and copiapite for the high-acid sections and goethite for the neutral to alkaline
stream rock coatings. However, these are very different systems chemically.
Lake Creek contains considerably less sulfur, and therefore, its waters tend to
precipitate sulfate, oxide, and hydroxide minerals in a textbook model with
changing pH zones with flow down-drainage and as neutral inflows are received.
The effluents from the Leadville District wastes are sulfur-enriched, and
carbonate-buffered, and consequently produce quite different sulfates such as
aluminite (Al sulfate) and amaranthite (Fe sulfate). Copiapite and jarosite are
restricted to ephemeral backwaters and small tributaries of the main river.

Hyperspectral and multispectral remote sensing data were acquired for these
areas using airborne and satellite sensors. Specific iron sulfate, iron hydroxide,
iron oxide, and aluminum hydroxide mineral species are only stable within certain
pH ranges and are indicative of stream pH at time of deposition. Along the
Arkansas River, tailings and Leadville wastes deposited within the floodplain are
mapped. These techniques assist in baseline characterization, evaluation of impact
of ARD on watersheds, and planning and prioritization of remedial activities.

Additional Key Words: AVIRIS, ARD, tailings, SpecTIR, watershed

1Paper 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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CO, 80203; David A. Bird is with the Colorado Geologic Survey; Frederick B. Henderson III is with
HENDCO Services, Nathrop, CO, 81236; Eric C. Prosh was with Spectral International Inc.
SUSTAINABLE MINE DRAINAGE TREATMENT THROUGH THE PASSIVE PRODUCTION OF SALEABLE IRON OXIDE SOLIDS

Robert S. Hedin

Abstract. Iron is the most common metal contaminant of coal mine drainage. Its treatment creates a metal-rich sludge whose management accounts for a substantial portion of the total treatment costs. For decades, researchers have searched unsuccessfully for cost-mitigating uses for mine drainage sludge. This paper describes our progress in the development of a passive treatment process that yields iron oxide sludge that has valuable pigmentary characteristics. Samples of iron solids were collected from a variety of environments. All samples from chemical treatment systems were impure because of the coprecipitation of multiple chemical parameters. Only passive treatment systems yielded sludge pure enough to be considered for pigmentary applications. At several sites, the purity of the samples from passive systems was substantially decreased by the presence of alumino-silicate minerals introduced by inflows of surface water containing sediment. Mechanical and moderate chemical treatment, that was intended to accelerate iron oxidation without the precipitation of non-target elements, caused the precipitation of calcium-containing minerals that lessened the pigment strength. Solids collected from passive systems where the pH ranged below 6 were pure, but were weak pigments. Saleable pigment-quality iron solids were produced from passive systems where sediment inflows were minimal and the pH was maintained between 6 and 7. A treatment system that produces saleable iron solids through passive treatment techniques has the potential to provide self-sustaining mine drainage treatment.

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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ABANDONED MINES IN CANADA

Charlene M. Hogan and Gilles A. Tremblay

Abstract: Mining has been central to the Canadian economy for over 100 years and Canada is a supplier of mineral commodities worldwide. The long history of mining in Canada has resulted in more than 10,000 orphaned and abandoned mine (OAMs) sites requiring varying degrees of rehabilitation. The legacy of OAMs, with the associated environmental liability, human health concerns and the financial costs of clean up, is a serious issue facing Canada. OAMs exist within all mining jurisdictions in Canada.

The National Orphaned/Abandoned Mines Initiative (NOAMI) was established in 2002 and is a co-operative Canadian program that is guided by an Advisory Committee consisting of the mining industry, federal/provincial/territorial governments, environmental non-government organizations (NGOs) and Aboriginal Canadians. The advisory committee's role is to assess key issues and put forward recommendations concerning collaborative approaches and partnerships in the implementation of remediation programs across Canada. Five task groups were established to examine key issues. These consist of information gathering (towards an inventory and national definition), funding approaches, and legislative barriers to collaboration, community involvement, and guidelines to legislative and jurisdictional review.

Canada is well known for establishing multistakeholder initiatives to address issues of national importance. This model of cooperation among industry, various levels of government, NGOs and/or Aboriginal Canadians is now being used internationally. NOAMI is a good example of diverse stakeholders coming together to address the legacy of past mining practices and to advance the objectives of sustainable development.

Several provinces in Canada have already taken significant steps to address abandoned mines in their respective jurisdictions, and the information garnered from these activities will be invaluable in addressing these issues on a national scale. This paper presents an overview of the issues surrounding abandoned mines in Canada, and national and provincial programs that have been initiated.

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ALUMINUM PRECIPITATION IN ACIDIC PIT LAKES AT THE GIBBONS CREEK LIGNITE MINE, TEXAS, USA: FIELD OBSERVATIONS vs. LABORATORY SIMULATIONS

Jan K. Horbaczewski

Abstract. In April 2002, a precipitate was discovered in two acid end pit lakes that were in the process of being neutralized at Gibbons Creek lignite mine in east-central Texas. The precipitate was found in shallow water on the shoreline shelves of the ponds. It had the form of extensive mats of a light brown, finely-layered gelatinous material resting lightly on the detrital shelf material. Chemical analysis of the precipitate revealed that it was composed mostly of aluminum with subordinate iron and minor amounts of Ca and SO$_4$. The stoichiometry of the components and the chemical environment suggests that the aluminum is most probably in the form of a hydroxide (gibbsite) rather than an aluminosulfate. The shelves on which the precipitates were found had formed in December 2001. The precipitates had therefore accumulated over a period of 3-4 months. In this period, the pH of one pond (Pond A2P-1) had increased from pH 4.0 to 4.7 and that of the other (Pond A2P-2) from pH 4.5 to 5.0. The field observations are supported by earlier laboratory titrations of originally more acid water (as of December 1, 2000) from the same lakes. The titrations had shown a very strong buffering effect between pH 4.6 and 4.9 that had been interpreted as due to the precipitation of aluminum hydroxide. However, there are important differences between the field- and laboratory-scale reactions. It was found that the laboratory could not simulate the kinetics of field reactions, especially the effects of aging and polymerization of aluminum hydroxide, nor the openess of field systems with their virtually inexhaustible supplies of reactants.

Additional Key Words: gibbsite, aluminum hydroxide, aluminosulfate, buffering effect, aging, polymerization.

1 Poster 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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SAVAGE RIVER MINE - PRACTICAL REMEDIATION WORKS

Bruce J. Hutchison & David Brett

Abstract. Australian Bulk Minerals purchased the Savage River Mine in 1996 from the Tasmanian government. The mine operates in a wet temperate environment in steep terrain and has an historic environmental legacy of acid rock drainage. Mining personnel have worked with the government to remediate the historic legacy and along the way have developed simple mine planning and mining techniques to maximize the cost effectiveness of the operation. This paper outlines several of those techniques, including ore and waste handling procedures, alkaline flow-through construction, waste dump construction and remediation of an historic acid producing waste dump by construction of combined water shedding and alkaline side covers.
COMPARISON OF MEASURED AND MINERALOGICALLY PREDICTED VALUES OF THE SOBEK NEUTRALIZATION POTENTIAL FOR INTRUSIVE ROCKS

John L. Jambor, John E. Dutrizac, Mati Raudsepp

Abstract. Twelve specimens of intrusive rocks, ranging from granitic to ultramafic, were ground and subjected to the static-test neutralization-potential (NP) protocol so that the results could be compared with those computed by using the NP values previously obtained by Sobek tests of the constituent minerals. The quantitative mineralogy of the rocks was determined by Rietveld refinements of X-ray powder diffraction data, and was supplemented by optical microscopy, fizz tests, and analyses of total carbon to determine the presence of carbonate minerals. Despite the igneous nature of the suite, most samples were found to be carbonate-bearing; optical microscopy and fizz tests of the coarse (minus 6 mm) fractions were observed to be more sensitive to the presence of carbonates than was the minus 60-mesh fraction that is used in the Sobek protocol. For some minerals, notably olivine and serpentine, the acid-digestion period in the Sobek test has a pronounced effect on the resulting NP, and this part of the test protocol is in need of new standardization. Mineralogical prediction of the NP values is sensitive to the composition of the plagioclase because these feldspars are typically a major component of igneous rocks and the NP of the calcic end-member, anorthite, is about 12 times that of the sodic end-member, albite.

Additional Key Words: static tests, acid drainage, particle size, acidification period, plagioclase composition, Rietveld method, quantitative mineralogy, calculated NP.

1Paper 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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THE ROLE OF DISSOLVED CARBON DIOXIDE IN GOVERNING DEEP COAL MINE WATER QUALITY AND DETERMINING TREATMENT PROCESS SELECTION

Adam P Jarvis

Abstract. Field and laboratory measurements of mine waters emerging from abandoned deep coal mines in the UK have shown that CO2 partial pressures (pCO2) may be more than 100 times greater than atmospheric levels. Measured values of acidity vary significantly with time due to degassing of CO2 from such samples. The evolution (i.e. decrease) of pCO2 with time is described. The significance of these findings for mine water treatment process selection is discussed, and plans for future research in this area are outlined.

Additional Key Words: acidity, alkalinity, pH, bicarbonate, carbonic acid, thermodynamic mass action

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INFLUENCE OF PERCHED WATER TABLES BELOW MINE WASTE ROCK ON METAL LOADINGS TO STREAMS, PROSPECT GULCH, SAN JUAN COUNTY, COLORADO

Raymond H. Johnson, Laurie Wirt, Robert R. McDougal, and David L. Fey

Abstract. Infiltration through mine waste to a receiving stream is an important source of metal loading in Prospect Gulch, a steep alpine catchment in southwestern Colorado. Integrated hydrologic, geochemical, and geophysical studies identify contaminant plumes beneath waste dumps and indicate that saturated colluvium beneath mine waste overlies unsaturated bedrock, which becomes saturated with depth. Subsurface geology influences ground-water flowpaths and the occurrence of metal-rich acid drainage is related to the distribution of hydrothermally-altered terrain as well as mining disturbances. The geochemistry of water-bearing layers is compared with stream inflows to determine flowpaths and source(s) of ground water supplying the stream.

Hydrogeochemical data are derived from: 1) multilevel monitoring well installations, 2) shallow piezometer installations, 3) water level and geochemical sampling of wells and piezometers, 4) flow and geochemical sampling of streams, and 5) geochemical sampling of seeps and springs. Geophysical data include shallow resistivity and seismic profiles near the mine waste areas. Integration of these data identifies a perched water table system below the mine waste that occurs in colluvial material (to 15 meters) overlying unsaturated bedrock. At approximately 50 meters, the bedrock becomes saturated as part of a deeper ground-water flow system. Distinct ground-water plumes with high metal concentrations form in the colluvial material below the mine waste. These plumes are identified by both the ground-water samples and geophysical profiles and appear to discharge into the surrounding streams directly rather than recharge the deeper ground-water system. The geochemistry of the deeper ground-water system is consistent with water-rock interaction with the surrounding hydrothermally-altered, sulfide rich, volcanic rocks. Based on well- and stream-sample geochemistry, the deeper ground-water system discharges to lower Prospect Gulch and in nearby Cement Creek, just below Prospect Gulch.

Additional Key Words: acid mine drainage, abandoned mine lands, subsurface impacts, hydrogeochemistry

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

2Raymond H. Johnson is a Hydrogeologist at the U. S. Geological Survey, Denver, CO, 80225. Laurie Wirt is a Hydrogeologist at the USGS Denver office, Robert R. McDougal is a Geophysicist at the USGS Denver office, David L. Fey is an Analytical Chemist at the USGS Denver office.
COMPARISON OF APATITE II™ TREATMENT SYSTEMS AT TWO MINES FOR METALS REMOVAL

A. Lynn McCloskey, Bryony Stasney, Judith Wright, James L. Conca, Neal Yancey, Norma Lewis, Helen Joyce

Abstract. Two abandoned lead-zinc mine sites, the Nevada Stewart Mine and Success Mine, are located within the Coeur d’Alene Mining District, in northern Idaho. Apatite II™ (US Patent Number 6,217,775), a form of cleaned fishbone apatite material, was used as the treatment media in both treatment systems to treat metal-laden water. The difference in water quality from the two lead-zinc sites resulted in different design requirements for the two sites. This poster presentation will provide a comparison of these Apatite II Treatment Systems from system design and performance monitoring perspectives. Lessons learned during operation of the treatment systems and recommendations for future applications of Apatite II will also be presented.

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THE INFLUENCE OF CLIMATE, VEGETATION, LAYER THICKNESS, AND MATERIAL PROPERTIES FOR PERFORMANCE OF THE COVER SYSTEMS AT THE GOLDEN SUNLIGHT MINE

Fernando F. Junqueira, G. Ward Wilson, Craig Nichol, and Shannon Dunlap

Abstract. Golden Sunlight mine is located northeast of Whitehall, MT. Two cover systems were installed on the west waste rock complex and tailings area in order to minimize water infiltration and acid drainage. The covers were designed to function as a store-release system and are composed of coarse and fine materials being 0.80 m thick on the waste rock and 1.8 m thick at the tailings area. In order to study the influence of thickness, material properties, vegetation and climate on the performance of the cover systems, a laboratory testing program was carried out to identify the properties of the cover at different depths. In addition, thermal conductivity sensors were installed at three field monitoring stations located on the waste rock dump and tailings area in order to evaluate the variation of suction in the cover profiles. These data were used to calibrate a numerical modeling program that assessed infiltration rates through the covers under different vegetation and climate conditions. The simulation results were used to correlate internal variations in grain size and hydraulic conductivity with cover performance in terms of measured suction profiles and infiltration rates.

The results show that vegetation plays a critical role in cover performance and becomes most important during wet and very wet years. The simulations and field measurement also revealed that the internal properties of the cover control infiltration patterns, showing upward and downward fluxes at different zones within the cover. It is shown that while increasing layer thickness reduces the dependence of cover performance on vegetation conditions, the establishment and sustainability of vegetation remains most important with respect to satisfactory long-term performance of store-release cover systems.

Additional Keywords: Store-release cover, numerical modeling

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

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FIELD MEASUREMENTS OF SURFACE GAS FLUXES AND SURFACE-WATER CONDITIONS FOR MINE WASTE ROCK MANAGEMENT

L.K. Kabwe, G.W. Wilson and J.M. Hendry

Abstract. Field measurements of the variations of surface gas fluxes (e.g., O₂ and CO₂) and waste-rock surface drying and evaporation are critical in the development of a long-term management plan for mine wastes. However, such measurements on waste-rock piles are lacking. Previously, we tested and verified a dynamic closed chamber (DCC) method in minicosms and a mesocosm and then applied at a field-scale to quantify the CO₂ efflux at the Key Lake uranium mine, northern Saskatchewan. In this study we investigated the short-term effects of heavy rainfall events on the near surface waste-rock water contents and the resultant CO₂ efflux from the Deilmann north waste-rock pile (DNWR). We also investigated the short-term evaporative fluxes using SoilCover numerical model. The corresponding average O₂ flux into the pile was estimated using the measured CO₂ efflux data and the reported kinetic ratio (1O₂:0.2CO₂) determined from samples collected from the DNWR. Using the average value of the measured CO₂ efflux (217 mg m⁻² h⁻¹) the corresponding O₂ flux into the DNWR was calculated to be 789 mg m⁻² h⁻¹. Results showed that the CO₂ gas efflux was dramatically reduced after heavy rainfall events, however, the impart was of relative short duration. This behavior was attributed to hydraulic properties of the waste-rock material. These data can be of value in the long-term development of a plan for mine waste management.

Additional Key Words: gas fluxes, waste-rock, unsaturated soil.

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

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NATURAL IRON HYDROXIDE PRECIPITATES: THEIR ACID GENERATION POTENTIAL IN GROUND WATER ASSOCIATED WITH TAILINGS

Margarete Kalin\textsuperscript{2}, Andrew Fyson\textsuperscript{2}, Günther Meinrath\textsuperscript{3}

\textbf{Abstract.} Iron hydroxide precipitates, generated from acid mine drainage adhere to surfaces in tailings and waste rock piles and accumulate as sludges in ditches and in pond sediments in mine waste management areas. Such precipitates undergo a series of transformations which lead ultimately to the stable mineral goethite. Ground water from piezometers in an below tailings containing 41 \% pyrite were stored for 4 years unpreserved in their original, un-sterilized sampling bottles reached pH values around 1. The stored water with the iron precipitates have been able to support Fe-oxidizing and Fe-reducing bacteria and similar microbial populations were identified on slides which were immersed into the piezometers from the same tailings site. A clear relationship between microbial activity and Fe(III) mineral compositions in the iron precipitates from the stored samples and from sludges accumulating in a ditch precipitating from the effluent from underground workings at the same site, could not be established. The relevance of the microbial activity in the formation of secondary minerals occurring in ground water in and below tailings and accumulating on the surface is discussed. The high variability of the output of geochemical modelling (PHREEQC) to the modelling input allowed a wide variety of possible interpretations.

\textbf{Additional Key Words:} microbial activity, iron hydroxides, alteration, acid generation potential, geochemical modelling

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502
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USING AIRBORNE ELECTROMAGNETIC SURVEYS TO IDENTIFY POTENTIAL HAZARDS AT COAL WASTE IMPOUNDMENTS: EXAMPLES FROM WEST VIRGINIA

Vladislav Kaminski, Richard W. Hammack, William Harbert, Terry Ackman, James Sams and Garret Veloski

Abstract. Mine impoundments have in the past been a cause of catastrophic loss of life and destruction of property. To characterize this potential hazard, helicopter-mounted electromagnetic (HEM) surveys of coal waste impoundments were completed to identify fluid saturated zones within coal waste and to delineate the paths of filtrate fluid flow beneath the decant pond, through the embankment, and into adjacent strata or receiving streams. We also attempted to identify flooded mine workings underlying or spatially adjacent to the waste impoundment areas. In this effort, the National Energy Technology Laboratory of the United States Department of Energy (http://www.netl.doe.gov) conducted HEM surveys of 14 coal waste impoundments in southern West Virginia. Five electromagnetic frequencies were used in our surveys (385, 1700, 6536, 28120 and 116300 Hz) and processed using different inversion techniques to determine apparent conductivity depth images (CDI). Follow-up, ground-based resistivity surveys verified the results of the HEM survey. Overall, HEM and ground-based geophysical surveys proved to be effective in delineating the phreatic surface, determining seep locations, locating blockage in engineered drains, imaging areas of unconsolidated slurry, locating areas where process water has invaded adjacent aquifers, potentially depicting the possible location of flooded underground mine workings, locating infiltration zones into the abandoned mines and determining the spatial extent of impoundment impact.

1 Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502 15129

2 Vladislav Kaminskiy and William Harbert are Research Associates, National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, PA and a graduate student and Associate Professor respectively at the Dept. of Geology and Planetary Science, Univ of Pittsburgh, PA, USA 15260, Richard Hammack, Terry Ackman, James Sams and Garret Veloski are researchers of the Water and Energy Team, National Energy Technology Laboratory, Pittsburgh, PA, USA 15236-0940.
SENECA SURFACE COAL MINES--A 40 YEAR CASE STUDY IN RECLAMATION TECHNIQUES— TRIUMPHS AND FAILURES: TWO STUDIES OF SHRUB ESTABLISHMENT

Roy A. Karo

Abstract: Seneca Coal Co. operates the Seneca II, Seneca II-W, and the Yoast Mines in Northwest Colorado, 6,300 ft to 8,500 ft elevation. The reclaimed land was seeded with a diverse mix of native and non-native grasses and forbs. Also, and extensive shrub reestablishment effort was undertaken. Coal production ceased in 2005 leaving 4000 acres of reclaimed land. The success of the reclamation program at Seneca Coal Co. is evident even within a climate of changing regulations, high altitude, and very steep slopes. The Wadge Pasture, a block of reclaimed land approximately 15 years old, was measured for revegetation success in 2004, Study #1. Colorado State University, Colorado Division of Minerals and Geology, and Seneca Coal Co. cooperated in a study of shrub establishment techniques and the results are presented in Study #2.

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SUCCESSFUL DEWATERING OF ACID MINE DRAINAGE MATERIALS\textsuperscript{1}

Peter Kaye\textsuperscript{2}

Introduction

Many states are faced with the problem of dealing with both old inventories of stock-piled residues, as well as those materials recently excavated in order to provide roads and access to mining areas. The leachate from these tailings produces an iron oxide material that will, if not monitored and controlled, flow into our drinking water, streams, and rivers.

Geosynthetic Products

Proper detection and treatment of the material through state policy and environmental management will prevent this migration. Several attempts have been made to volume-reduce and dewater these residuals, in order to place as little as possible in the storage impoundments for tailings/sludge or to the local landfills. The use of a geosynthetic polypropylene material, which is fabricated into a cylindrical tube called a Geotube\textsuperscript{®} container, has received widespread attention over the past several years. This specially woven fabric membrane allows the filtrate to escape while containing the solids. Volume reductions of 75- to 85% have been achieved with acid mine drainage materials. Several companies are providing experience, engineering, and software for sizing, technical assistance in testing, chemical usage, and field installations.

Project Experience

On a recent project for the PA DOT, the consulting engineer required assistance with an emergency acid mine drainage project for the Highway 99 construction. Excavated material for the highway construction had been stacked nearby for further use by the contractors until the presence of pyritic materials was determined, which would cause drainage of contaminated materials from this large volume of sludge/slurry. The slurry material was concentrated in several holding areas or storage lagoons.

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} 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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MICROBIAL ACTIVITY IN FABRICATED SOILS FOR LANDSCAPE REHABILITATION

Valentine Kefeli², Maria Kalevitch³ and Margaret Dunn²

Abstract. Fabricated soil is a mixture of organic and inorganic components creating a substrate rich in aluminosilicates, carbon, nitrogen, phosphorus, and potassium. A year after incorporation into coal mine soil, dramatic increases in bacterial heterotrophic microflora (BHM) and equally dramatic decreases in mold colonies were observed. Later decreases in mold colonies were particularly noted in plots containing poplar and willows, whose root excretions appear to act as natural antiseptics. BHM may, in turn, play an important role in the transformation of phenolic inhibitors (allelopathogens) thus maintaining healthy soil-plant relationships and emphasizing the role of fabricated soils in landscape rehabilitation.

Additional Keywords: Mine land reclamation, microbial components

¹Poster 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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LESSONS LEARNED FROM THE U.S. GEOLOGICAL SURVEY
ABANDONED MINE LANDS INITIATIVE – 1997-2002

Briant A. Kimball, Stanley E. Church, and John M. Besser

Abstract. Growth of the United States has been facilitated, in part, by hard-rock mining in the Rocky Mountains. Abandoned and inactive mines cause many significant environmental concerns in hundreds of watersheds. Those who have responsibility to address these environmental concerns must have a basic level of scientific information about mining and mine wastes in a watershed prior to initiating remediation activities. To demonstrate what information is needed and how to obtain that information, the U.S. Geological Survey implemented the Abandoned Mine Lands (AML) Initiative from 1997 to 2002 with demonstration studies in the Boulder River watershed in Montana and the Animas River watershed in Colorado. The AML Initiative included collection and analysis of geologic, hydrologic, geochemical, geophysical, and biological data. The synergy of this interdisciplinary analysis produced a perspective of the environmental concerns that could not have come from a single discipline. Two examples of these perspectives include (1) the combination of hydrologic tracer techniques, structural geology, and geophysics help to understand the spatial distribution of loading to the streams in a way that cannot be evaluated by monitoring at a catchment outlet, and (2) the combination of toxicology and hydrology combine to illustrate that seasonal variability of toxicity conditions occurs. Lessons have been learned by listening to and collaborating with land-management agencies to understand their needs and by applying interdisciplinary methods to answer their questions.

Additional Key Words: Hydrothermal alteration mineralogy, metal loading, ecotoxicology, risk assessment, science-based decisions

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

UTILIZATION OF MOBILE COMPUTING AND GIS TO EVALUATE RECLAIMED LANDS IN MISSOURI

Kwang “Min” Kim, Kale Horton, Perry Pursell, and Kevin Garnett

Abstract. Global Positioning System (GPS) integrated mobile geographic information system (GIS) technology is becoming increasingly popular in coal mining regulatory programs because of its ability to provide instant and accurate data updates and ways to verify information associated with mining and reclamation activities. Many state and federal regulatory programs have begun using or considering use of the mobile GIS in permitting, inspection, reclamation, and bond-release activities. Verification of permit boundary, identifying soil probe and water sample locations, and assessment of revegetation status on reclaimed lands are a few examples of how the mobile GIS technique can be applied. For the purpose of illustrating usefulness of mobile GIS in coal mining related field work, inspection activities on an active mine site and assessment of the postmining land uses and revegetation status on reclaimed lands conducted by the Office of Surface Mining / Mid-Continent Region (OSM/MCR) in Missouri are used as case studies in this paper.

During the spring of 2005, Alton Field Division of OSM/MCR initiated protocol of mobile inspection, which adapted the mobile GIS concept into mine inspections. Stylistic™ tablet computer by Fujitsu with Wide Area Surveillance Satellite (WASS) enabled Haicom™ GPS card along with ArcPad™ software by Environmental Systems Research Institute (ESRI) were used in the prototype mobile inspection. Meier and others, 2004 reported that Fujitsu Stylistic™ tablet computer has very good indoor and outdoor display quality and works well with Haicom™ GPS card and ArcPad™. Prior to each mine inspection, ArcMap™ software by ESRI was used to view and assess necessary GIS data layers (aerial photograph, quadrangle map, roads, permit boundary, mine pit boundaries, and etc.) in the office. Then the area of interest was cropped and exported as ArcPad™ project folder. The ArcPad™ project folder was later loaded into the tablet computer to be used in the field. For easier data input, ArcPad Builder™ software by ESRI was used to create customized data entry forms. This mobile computing technology provides more efficient ways of implementing the Surface Mining Control and Reclamation Act (SMCRA).

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COMPUTATIONAL METHODS FOR ACID MINE DRAINAGE MANAGEMENT: SIMULATION OF HYDROGEOCHEMICAL PROCESSES IN ABANDONED UNDERGROUND COAL MINES

Natalie A.S. Kruse, Paul L. Younger, and Vedrana Kutija

Abstract. Predicting post-mining water quality is a key task in managing mine drainage. The most scientifically-defensible approach would be to undertake thermodynamics-based modeling of coupled geochemical and hydrodynamic processes occurring in flooded and partly flooded underground workings. Most models currently in use make the fatal assumption of local equilibrium, or else do not include all important geochemical and geometrical components of an abandoned mine system. Hydrologic and geochemical data have been incorporated into a model (POllutant Sources & Sinks in Underground Mines) that models one-dimensional reactive transport along a mine roadway. POSSUM is an object-oriented program that models the evolution of mine water quality, accounting for contaminant sources and sinks, water level changes (due to rebound and seasonal fluctuations), reaction kinetics, variable flow regimes, infiltration through porous media, and inflow from secondary roadways. The main metals included in POSSUM’s analysis are Fe, Al, Mn, Ni, and Zn. Additionally, carbonates, including limestone, ankerite and siderite, and silicates, including K-feldspar, anorthite, albite and muscovite are represented in POSSUM. Reversible sorption is also accounted for. Contaminant transport is solved using the NOAH 1-D program developed at University of Newcastle. POSSUM solves for concentrations in both the aqueous and solid phases using sequential iterations of finite difference numerical methods. Data sets from the National Coal Mining Museum in Wakefield and Coal Authority boreholes have been collected for comparison with model results. In contrast to pre-existing models, POSSUM couples kinetically controlled multi-component reactions with variable transport and will further the ‘state of the art’ by improving the defensibility of predictions of water quality changes over time.

Additional Key Words: reactive transport modeling, object-oriented programming, random walk method

1Paper 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 (ASMRE), 3134 Montavesta Road, Lexington, KY 40502

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SUCCESSFUL IMPLEMENTATION AND OPERATION OF A PASSIVE TREATMENT SYSTEM IN AN EXTREMELY COLD CLIMATE, NORTHERN QUEBEC, CANADA

Nural Kuyucak, Francois Chabot and John Martschuk

Abstract. Seepage from tailings stockpiles at a decommissioned mine site in northern Quebec, Canada showed typical characteristics of acid rock drainage, requiring collection and treatment to be completed within a few months. The site is remote and without power, making the application of a chemical (active) treatment unfeasible due to significant required resources in both capital and time. Passive treatment systems are a reasonable alternative, despite the extreme winter conditions prevalent at the site, and were implemented at the site in 2004.

During site clean up and preparation, a site-specific passive treatment facility was designed based on available data; it included a seepage collection system, anaerobic and aerobic cells, and a limestone filter. Organic nutrients required for the anaerobic fermentation and cultivation of sulphate reducing bacteria were selected from locally available materials. A suitable mixture was prepared and preconditioned. The treatment facility was installed and commissioned in October 2004. The results to date indicate that a properly designed passive system can produce water quality in compliance with the provincial government regulations. Experience gained from the work is discussed.

Additional Key Words: Acid rock drainage, acid mine drainage, remote sites, seepage, sulphate reducing bacteria, limestone drain, limestone filter, organic nutrients, wood chips, manure, hay, aerobic cell, anaerobic cell.

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ANTIMONY LEACHING FROM STIBNITE AND COMPLEX ORES

Y.T. John Kwong, Allen Pratt and Gianluigi Botton

Abstract. To shed light on the leaching of Sb from mine wastes containing stibnite, two series of experiments were conducted. In one experiment, polished slabs of a museum-grade stibnite and a mixed-sulfide ore sample containing 28% Sb were subjected to accelerated weathering at 100% humidity and 31-35°C for 37-44 days. After leaching with distilled water, insoluble weathering products remaining on the test specimens were examined with a variety of spectroscopic techniques including transmission electron microscopy, electron energy loss spectroscopy, synchrotron-radiation X-ray photoelectron spectroscopy and X-ray absorption near-edge spectroscopy. In another experiment, semi-polished slabs of a mixed-sulfide ore containing 3% Sb were submerged in distilled water and the evolution of leachate chemistry was monitored over a period of 147 weeks. The results show that galvanic interaction plays an important role in dictating the extent of Sb leaching under both subaerial and subaqueous conditions. Thus, detailed mineralogical characterization is indispensable in predicting the leaching of Sb from mine wastes containing mixed sulfides.

Additional Key Words: simulated weathering, sensitive surface analyses, galvanic sulfide oxidation.
PYRITE OXIDATION RATES FROM HUMIDITY CELL TESTING OF GREENSTONE ROCK

Kim A. Lapakko² David A. Antonson²

Abstract. Fourteen samples of pyrite-bearing Archean greenstone rock (d < 6.35 mm, 0.08 ≤ FeS₂ ≤ 2.25 wt. %) were characterized and subjected to laboratory dissolution testing for periods of 154 or 204 weeks. Rates of pyrite oxidation were determined based on the observed rates of sulfate release between weeks 20 and 60 and the calculated pyrite surface areas exposed. The pyrite surface areas exposed were determined based on the particle size distribution, sulfur content of individual size fractions, and percent pyrite liberation. The pyrite oxidation rates, normalized for exposed surface area, ranged from 4 × 10⁻¹⁰ to 18 × 10⁻¹⁰ mol m⁻² s⁻¹ and tended to increase as drainage pH decreased from 7.3 to 3.3. For eight rock samples with median pH values above 6.0, rates were roughly 0.6 to 1.3 times those predicted in the literature for the abiotic oxidation of pyrite by oxygen. Median pH values for the remaining six samples ranged from 3.3 to 5.0, and pyrite oxidation rates were roughly 2 to 8 times the published abiotic rates, suggesting the influence of oxidation by ferric iron.

Additional Key Words: kinetics, kinetic tests, mine waste drainage, drainage quality prediction

¹Paper 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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EFFECTS OF PARTICLE SIZE ON DRAINAGE QUALITY FROM THREE LITHOLOGIES

Kim A. Lapakko, Jennifer N. Engstrom, and David A. Antonson

Abstract. Samples of three different waste-rock lithologies (olivine norite, diatreme, and adularized mudstone) were selected to determine the relationship between particle size and acid production for each of three lithologies. The three samples were characterized with respect to chemistry, mineralogy, and petrology. Five to six particle size fractions from each lithology were subjected to dissolution testing for typical periods of 335 to 465 weeks. The dependences of (1) drainage pH, (2) time of dissolution prior to drainage acidification, (3) fraction of Ca and carbonate minerals reacted prior to drainage acidification, and (4) relative rates of acid production and neutralization on particle size varied among the three rock types. For example, drainage pH values from fine fractions of the olivine norite decreased more rapidly than those from coarse fractions, while the opposite trend was observed for the adularized mudstone. Drainage pH values from the diatreme presented a third trend, with no strong dependence of the temporal pH variation on particle size. The dependence of drainage pH and related variables on particle size was due to the influence of particle size reduction on the relative abundance of exposed acid-producing and acid-neutralizing mineral surface areas. This influence is dependent on minerals present in waste rock, their grain size, and occurrence, and must be considered in interpretation of kinetic test results and modeling these results for field application.

Additional key words: mine drainage, acid drainage, ARD, drainage quality prediction, waste rock, kinetic testing, diatreme, olivine norite, mudstone

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MINE CLOSURE PLANNING IN PERU¹

Henri Letient², Rob Marsland, Marco Marticorena, and Harvey McLeod

Abstract. Recent legislation provides comprehensive closure regulations in Peru. The conceptual closure plan for the Antamina Cu/Zn mine, developed initially as part of the EIA, was updated to meet the new requirements. This included predicting future water quality, based on site operational monitoring data and large scale field kinetic tests, as the basis for design of a water treatment system. Cost estimates for water treatment, facility demolition and waste dump reclamation, etc., were prepared. This case study outlines the key components of the new legislation and illustrates the importance of designing and developing a mine with the ultimate closure in mind.

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IN SITU CHEMICAL AND BIOLOGICAL TREATMENT LEADING TO SUCCESSFUL WATER DISCHARGE FROM ANCHOR HILL PIT LAKE, GILT EDGE MINE SUPERFUND SITE, SOUTH DAKOTA, U.S.A.1

B. T. Park, K. W. Wangerud, S.D. Fundingsland, M.E. Adzic, N. M. Lewis2

Extended Abstract. The EPA Region 8 Superfund office and the EPA National Risk Management Research Laboratory (NRMRL) Mine Waste Technology Program (MWTP) have been conducting a field-scale technology demonstration of an in situ treatment of the Anchor Hill Pit lake at the Gilt Edge Mine Superfund site near Deadwood, South Dakota since March of 2001. The project goal was to develop cost and performance data of the treatment approach for potential application in long-term water treatment/management activities at the Gilt Edge site, as well as potential application at other similar sites. The Anchor Hill Pit initially contained approximately 265,000 cubic meters (70,000,000 gallons) of acidic mine water, with elevated metals (including iron, aluminum, selenium, copper, cadmium, and zinc), sulfate, and nitrate content and a pH of approximately 3. The water column was approximately 30 meters deep. The first step of the two-stage in situ treatment consisted of using a Neutra-Mill (essentially a floating lime slaker developed by Earth Systems, Pty. of Australia), to neutralize the pit pH to approximately 7 using lime (March 2001-May 2001). Following a short stabilization period, during which the pH “settled” to a value of approximately 5.0, a patented process for in situ pit lake treatment using an organic formulation of molasses, methanol, and proprietary ingredients was implemented as the second treatment step in May 2001 by Green World Science, Inc. (now licensed to ARCADIS US, Inc.) to create reducing conditions; stimulate bacterial activity for nitrate, selenium, and sulfate reduction; improve water quality; and create a stable system. Denitrification and sulfate reduction did occur, leading to much-improved water quality. The treatment phase of the project, along with site background information, is documented in Lewis (2003)3 and the reader is referred to that paper for treatment details. This poster focuses on subsequent efforts undertaken to discharge water from the pit from both above and below the chemocline; efforts undertaken to evaluate the pit for ongoing

Additional Key Words: pit lakes, Arcadis, in situ, treatment, acid rock drainage, Neutra-Mill

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A SIMPLIFIED METHOD FOR ESTIMATION OF JAROSITE AND ACID-FORMING SULFATES IN ACID MINE WASTES

Jun Li, Roger StC Smart, Russell Schumann, and George Levay

Introduction

In standard acid base accounting methods, estimation of net neutralizing potential (NNP) from acid mine wastes is made by subtracting the acid potential (AP) from the neutralizing potential (NP). The AP estimate is determined from the total %S assay x 30.6 assuming that all S reacts according to the pyrite oxidation stoichiometry (Equation 1). It is well recognised that this estimate can be incorrect when other sulfides and acid-forming sulfates are present in the waste (e.g. Paktunc, 1999; White III et al., 1999; Weber et al., 2004).

FeS$_2$ + $\frac{15}{2}$H$_2$O$_2$ $\rightarrow$ Fe(OH)$_3$ + 4H$^+$ + 2SO$_4^{2-}$ + 4H$_2$O  

(1)

This estimate can be improved by using the net carbonate value (NCV) sulfide S method (Bucknam, 1998; Lapakko 2002). The NCV method measures reactive sulfide S by heating the sample at 550°C for one hour to convert reactive sulfide to S dioxide (pyrolysis). The sulfide content is determined as the difference between total S in the sample and in the residue after heating. This method does not include recovery of potentially acid producing secondary sulfates formed from pyrite oxidation as present in many mine wastes. Therefore, content of the acid producing sulfates in the sample need to be determined in addition to the NCV method. The amount of acid produced per unit of oxidised pyrite from the sulfates depends upon the type of the sulfates formed under different reaction conditions. If iron precipitates of goethite or ferrihydrite form from the Fe$^{3+}$ produced in the oxidation, then the full 3 H$^+$ units of acidity are released. However, if oxidation is incomplete, reducing conditions are maintained or wetting/drying cycles occur, ferrous salts can form retaining stored acidity in the waste as seen in the MEND Waite Amulet study (Nesbitt and Jambor, 1998). If hydrolysis is incomplete, jarosite can precipitate at pH below about 3.5 releasing only 2 H$^+$ per Fe$^{3+}$ formed (van Breeman, 1976; Lapakko and Berndt, 2003). This is commonly found in weathered coal and laterite Ni mine wastes where the pyrite is often highly reactive, especially framboidal pyrite. Schwertmannite can also form from incomplete hydrolysis but since this releases 2.6 H$^+$ per Fe$^{3+}$ (Piene et al., 2000), the error is not as significant. If hydrolysis is complete, water

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SUSTAINABLE REMEDIATION OF ACID ROCK DRAINAGE BY
REGENERATING CLINOPTILOTITE

Loretta Y. Li, Min Chen and John Grace

Abstract: The popular remediation technique using limestone for acid rock drainage (ARD) treatment may be unnecessarily expensive, generate additional solid waste and not be optimally effective. An inexpensive and locally-available soil zeolite – clinoptilolite – has a high metal adsorption capacity and a significant buffering capacity. An earlier batch adsorption study from our laboratory demonstrated that clinoptilolite has a high adsorption capacity for copper, zinc and aluminum, adsorbing 131, 158 and 215 mg/kg clinoptilolite, respectively, from a local ARD at pH 3.3. If clinoptilolite sorbent could be regenerated by backflushing, it could then be reused on site. The main focus of this presentation is the removal of metals from loaded clinoptilolite by backflushing. Clinoptilolite adsorption capacity for Zn, pH stability and the effect of pH on adsorption of Zn were also investigated. Laboratory batch equilibrium tests (USEPA 1987) were used to investigate the pH dependence and adsorption/desorption characteristics of clinoptilolite.

So long as the pH > 2, the crystal structure of clinoptilolite was found to remain stable after small amounts of Al and Si were leached from it. Clinoptilolite has the ability to retain Zn ions, and the amount adsorbed is a function of the initial concentration of Zn in the solution and of the pH. This suggests that the clinoptilolite may be an ideal candidate for ARD remediation.

The metal loaded clinoptilolite can be effectively backflushed and reused. The desorption efficiency mainly depends on the type of extractants, pH and concentration. For cyclic absorption/desorption, the adsorption by clinoptilolite remained satisfactory for six and nine regenerations with EDTA and NaCl, respectively. After different degrees of exposure to ARD, the crystallinity of clinoptilolite based on XRD indicates that the structure of clinoptilolite remains intact. The water quality of the clinoptilolite treated ARD was tested for metal concentrations and it was found that the metal concentration was drastically reduced, with the degree of reduction depending on the treatment conditions. Clinoptilolite appears to be a promising agent for ARD leachate treatment, with significant potential cost advantages compared to current treatment systems.

The ARD problem at Pennask Creek along Highway 97C in the Thompson-Okanagan region is an ideal site for a case study of remediation based on clinoptilolite. There we compare experimental results for different configurations for field implementation using clinoptilolite. This case study will begin in the spring of 2006 with funding from the B.C. Ministry of Transportation and Highways.

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

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MODELLING OF A WASTE ROCK DUMP DESIGN TO CONTROL
ACID ROCK DRAINAGE AT THE SVARTLIDEN GOLD MINE,
NORTHERN SWEDEN

Claire M. Linklater, John W. Bennett and Neale Edwards

Abstract. The Svartliden Gold Project has developed a complex design for waste rock dumps on the site. The design proposes encapsulation of potentially acid-forming material as cells within un-reactive material. Acid-forming material will be categorised as high risk or low risk, and within the overall dump design, cells involving high risk material will include a lining comprising low permeability glacial till. Acid generation is to be controlled by inhibiting contact between the reactive materials and oxygen, which must be supplied via diffusion of gas from the outer dump surfaces to the interior of the cells. Construction of such a complex dump is non-trivial and careful consideration has been given to the predicted long-term performance of the proposed strategy.

This paper describes how modelling techniques have been applied to quantify the benefits of the more complex dump design when compared with alternative simpler designs. The long-term performance of the dump was modelled using SULFIDOX. SULFIDOX takes a two-dimensional representation of the dump, and simulates the temporal and spatial evolution of key chemical and physical processes, e.g. diffusion and advection of gaseous components, infiltration of water, mineral reactions, heat conduction. For this work, an improved version of SULFIDOX was used that extends the approach so that heterogeneity in the initial dump configuration can be represented, allowing cells and other structures within the dump to be modelled.

Using SULFIDOX, it was possible to quantify benefits that the proposed dump design for the Svartliden site would deliver, namely (i) a significant reduction in the magnitude of any short-term peaks in contaminant load and (ii) management of the load profile so that contaminant levels remain below certain thresholds throughout the lifetime of the dump.

Additional key words: sulfides, oxidation

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IN-SITU COAL PIT LAKE TREATMENT OF ACIDITY WHEN SULFATE CONCENTRATIONS ARE LOW

Mark A. Lund, Clint D. McCullough, and Yuden Yuden

Abstract: Pit lakes (abandoned flooded mine pits) represent a potentially valuable resource to mining companies, the environment and community, if appropriate water quality can be achieved. However, the water is often of low pH with high dissolved metal concentrations. In Western Australia coal pit lakes are acidic (pH 3–5) but with low concentrations of sulfate and metals.

Low sulfate concentrations prevent microbial sulfate reduction from reducing acidity in these lakes. However, stimulation of primary production and associated alkalinity generating processes may provide a cost effective and sustainable solution to the acidity problems. A field-scale experiment (with control) involving the treatment of in-situ macrocosms (~600 m³) in a small south-west, Western Australian coal mine lake with municipal mulch and phosphorus additions to enhance primary production was undertaken between June 2003 and June 2004. One macrocosm was treated with P additions, another with mulch, a third with mulch and P, and the untreated lake formed the control. Physico-chemical and algal (chlorophyll a) sampling of the macrocosms and lake occurred at monthly intervals.

The decomposition of mulch reduced nitrogen concentrations in the macrocosms to very low levels and necessitated supplementation with urea fertilizer. Phosphorus concentrations dropped rapidly after addition as it became bound to iron, organic matter and sediment. Although there was virtually no difference between treatments and control for most physico-chemical parameters measured (including pH), a PCA of the data showed that the addition of mulch sent the macrocosms on a different trajectory to the control. This difference was reflected in observations of increased abundance and diversity of biofilms and macroinvertebrates within the treated macrocosms.

In conclusion, the addition of mulch and phosphorus alone was not sufficient to increase the pH of Collie mine lakes, although it does provide a number of benefits for biota in the water. We therefore recommend that liming be used to increase pH, followed by organic matter and nutrient additions to stimulate primary production.

Additional Key Words: acid mine drainage, nutrients, phosphorus, phytoremediation, primary production.

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2 Mark Lund (Senior Lecturer), Clint McCullough (Research Fellow), and Yuden Yuden (MSc student) are members of the Centre for Ecosystem Management, and ML and CM are also members of the Centre for Sustainable Mine Lakes at Edith Cowan University, 100 Joondalup Drive, Perth, WA 6027, Australia.
PREDICTED VERSUS ACTUAL WATER QUALITY AT HARDROCK MINE SITES: EFFECT OF INHERENT GEOCHEMICAL AND HYDROLOGIC CHARACTERISTICS

Ann Maest, James Kuipers, Kim MacHardy, and Gregory Lawson

Abstract. The Environmental Impact Statements (EISs) for 70 large modern-era hardrock mines in the United States were reviewed to determine their predicted impacts to water resources. EIS predictions were then compared to actual water quality conditions for 24 of the 70 mines (case studies), and the effects of geochemical characteristics and hydrologic conditions on operational water quality were evaluated. Nearly all case study mines with close proximity to water resources and moderate to high potential for acid drainage or contaminant leaching had operational water quality impacts ranging from increases over baseline concentrations to exceedence of water quality standards, with most having exceedences of standards. EIS water quality predictions made after considering the effects of mitigations largely underestimated actual impacts to groundwater, seeps, and surface water. EIS water quality predictions made before the ameliorating effects of mitigations were considered were more accurate at predicting operational water quality. Of the case study mines with these inherent geochemical and hydrologic characteristics, at least three-quarters underestimated operational water quality impacts in their pre-mining EIS predictions.

1 Poster 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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WATER MIGRATION IN COVERED WASTE ROCK, INVESTIGATIONS USING DEUTERIUM AS A TRACER.¹

Joseph R. Marcoline², Leslie Smith, Roger D. Beckie

Abstract. A deuterium tagged rainfall event with a δD of +213 was applied to the top surface of an experimental covered waste rock pile in May of 2003. The tracer experiment was designed to resolve the spatial variability of infiltrating water and to estimate the magnitude and rate of flow within covered waste rock. The five meter high pile was deconstructed one year later and waste rock was sampled along vertical profiles at 10cm increments. Pore waters were extracted from the waste rock using the centrifugal method. The measured δD values range from -90 to background levels of approximately -130 with a few zones of locally high δD values deeper than three meters in the pile. Variability between individual vertical δD profiles are observed within the 8x8 meter area. The combination of the spatial variability and the deep δD values yield strong evidence for intermediate scale (~15 cm) preferential flow.

¹Paper 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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MEASUREMENT OF OXYGEN CONSUMPTION AND DIFFUSION IN EXPOSED AND COVERED REACTIVE MINE TAILINGS

Vincent Martin 2, Michel Aubertin, Bruno Bussière, Mamert Mbonimpa, Anne-Marie Dagenais, Mathieu Gosselin

Abstract. When sulphidic tailings are exposed to atmospheric conditions, oxygen can flow in the material where it will be consumed by oxidation reactions. This paper presents results from a project studying the in situ oxygen diffusion and consumption in tailings. It provides measured values for the oxygen reaction rate $K_r$ and the effective diffusion $D_e$ coefficients based on oxygen consumption and diffusion tests that are performed under various conditions. Based on the test results, the $K_r$ and $D_e$ values determined in situ are compared to values obtained through simple predictive models. Results indicate that the value of these two parameters is influenced by factors such as the degree of saturation $S_r$ and in situ porosity $n$. A lower $S_r$ or a higher $n$ may increase the oxygen flux toward the reactive tailings, which can increase the production rate of acid mine drainage (AMD).

Additional Key Words: Acid Mine Drainage, Mine Tailings, Fick’s Laws, Oxygen Fluxes, Reaction Rate.

1 Poster 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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MITIGATING AMD IMPACTS IN NEW ZEALAND USING ENGINEERED WETLANDS

Craig A. McCauley, Aisling D. O'Sullivan, Paul Weber and Phil Lindsay

Abstract. Coal mining in New Zealand has caused perturbation of water resources and biodiversity. Contaminants impairing local waterbodies include acidity, iron, aluminum, arsenic, manganese, nickel, zinc, copper, sulfate and suspended solids. Exposure of sulfur containing rocks, such as pyrite, to atmospheric oxygen during mining operations produces acid mine drainage (AMD). Sulfuric acid and metal acidity are generated and can accentuate metal mobilization and bioavailability. Metals favor the dissolved state in acidic environments but form less toxic precipitates when exposed to adequate alkalinity. Metal toxicity effects are synergistic dependent on metals speciation and their concentrations.

New Zealand is in the initial stages of acid mine drainage mitigation and has yet to develop proven treatment technologies. Implementation of passive treatment methods, such as engineered wetlands, have successfully reduced acid mine drainage impacts worldwide. Design criteria for these systems are improving while their limitations are well documented. We are currently collecting water quality and flow data from selected AMD-impacted sites. We are in the process of designing pilot-scale engineered wetland systems to ameliorate acid mine drainage in New Zealand. Sequential-treatment trains will be constructed and their performance evaluated in order to optimize design effectiveness.

New Zealand acid mine drainage characteristics and complex topography offer unique challenges for implementing treatment systems. The AMD typically contains very high aluminum concentrations (commonly exceeding 50 g/m$^3$) and has an aluminum to iron concentration ratio of three to one. Abundant steep topography can be exploited to create adequate driving head for implementing systems such as SCOOFI reactors while reducing and alkalinity producing systems can also be employed. Precipitation of up to six meters per year contributes to dynamic hydraulic characteristics and will offer unique design and treatment challenges.

Additional Key Words: aluminum, iron, water quality, New Zealand, acid mine drainage, coal mining, steep topography

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MICRO COSM TESTING OF MUNICIPAL SEWAGE AND GREEN WASTE FOR FULL-SCALE REMEDIATION OF AN ACID COAL PIT LAKE, IN SEMI-ARID TROPICAL AUSTRALIA¹

Clint D. McCullough², Mark A. Lund and Joel M. May

Abstract: Pit lakes (abandoned flooded mine pits) represent a potentially valuable water resource to mining companies, the environment and regional communities across arid inland Australia. However, the water is often of low pH with high dissolved metal concentrations.

The addition of organic matter to the pit lakes to enhance microbial sulfate reduction is potentially a cost effective and sustainable remediation strategy for these acid waters. However, the cost and availability of sufficient quantities of suitable organic substrates is typically limiting in these remote regions. Nevertheless, small quantities of sewage and green waste (organic garden waste) are often available in these areas from the regional towns which support the mines. This paper reports on preliminary microcosm laboratory experiments in preparation for the treatment of an acid (pH 2.2) coal mine pit lake in semi-arid tropical, inland north Queensland, Australia with municipal treated sewage and green waste.

A laboratory experiment using microcosms (acrylic tubes) containing acid pit lake water and sediment were treated as follows; controls (untreated), sewage, green waste and sewage and green waste. The pH increased to a maximum of 5.5 in 145 days in the green waste and sewage treatment, with notable decreases of iron, aluminium and toxic heavy metals. Our results indicated that the green waste was a key component in alkalinity production and heavy metal removal.

Additional Key Words: acid mine drainage, pit lakes, sulfate reduction, wetland, organic matter.

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THE EFFECT OF NEUTRALISATION METHOD AND REAGENT ON THE RATE OF CU AND ZN RELEASE FROM ACID ROCK DRAINAGE TREATMENT SLUDGES

Danny M. McDonald, John A. Webb, Robert J. Musgrave

Abstract. Neutralisation of Acid Rock Drainage (ARD) by adding an alkaline reagent produces sludges generally dominated by amorphous ferrihydrite, often with high levels of adsorbed heavy metals. The effect of neutralisation method and reagent on the long-term chemical stability of these treatment sludges was investigated experimentally using a relatively oxidised synthetic ARD (containing Fe[~70% Fe$^{3+}$], Al, Cu and Zn) with a variety of reagents and processes, and two reduced synthetic ARD compositions (Fe$^{2+}$, Al, Cu and Zn; Fe$^{2+}$, Cu and Zn) treated with hydrated lime. The sludges were all subjected to kinetic testing to determine the rate of Cu and Zn release at pH 4, simulating disposal in a moderately acidic pit lake. All sludges precipitated from the oxidised ARD by standard ARD neutralisation procedures and reagents (lime, limestone, Bauxsol, KB-1 and HDS lime) showed similar chemical stability, with an initial rapid rate of release of Cu and Zn (~50% of leaching in the first 5 minutes) that reduced over time, apparently exponentially. The Cu and Zn are adsorbed onto the surface of the amorphous ferrihydrite present.

Sludges initially precipitated as ferrous hydroxide and then oxidised may contain a finely crystalline goethite component; if the ARD was Al-free the crystalline content is greater and coarser-grained and may consist of magnetite as well as goethite. Leaching of zinc from these crystalline sludges can be as much as an order of magnitude less than from sludges precipitated as ferric hydroxide, due to the incorporation of Zn within the mineral structure. Copper is more readily released from the sludges with a higher goethite/magnetite content, because it is adsorbed on the crystallite surfaces. However, it appears that Al-rich goethite can incorporate Cu, reducing its leachability.

Thus, modifications to the ARD treatment procedure, in particular control of oxidation state and Al levels, can substantially increase the crystallinity and improve the chemical stability of the sludge precipitated, and have a much greater influence on sludge leachability than the neutralisation agent used. These modifications are probably applicable to any water treatment sludges formed by pH adjustment.

Additional Key Words: ARD, neutralisation, sludge, leaching, magnetite, goethite, crystallinity, KB-1, Bauxsol

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CHARACTERIZATION OF GOATHILL NORTH MINE ROCK PILE, QUESTA MOLYBDENUM MINE, QUESTA, NEW MEXICO


Abstract. Rarely do rock pile characterization methods allow for examination and sampling of the interior of large rock piles in-situ. The regrading of the Goathill North (GHN) rock pile at the Questa mine provided a unique opportunity to examine and sample the interior of a large rock pile through the construction of trenches cut into the rock pile as earth-moving progressed. Maps of each bench were created to document the different stratigraphic units, including the thickness, dip, and extent of the units. Units were defined based on grain size, color, and other physical properties. Units were correlated between benches and downward through the series of successively excavated trenches. Typically, paste pH increased with distance from the outer, oxidized zone (west) towards the interior units (east) of the GHN rock pile. The outer zone was oxidized (weathered) based upon the white and yellow coloring, low paste pH, presence of jarosite and gypsum, and absence of calcite. However, the oxidation/reduction (weathering) state in the interior zone is not yet determined. The base of the rock pile closest to the bedrock/colluvium surface represents the oldest part of the rock pile since it was laid down first. Portions of the base appeared to be nearly or as oxidized (weathered) as the outer, oxidized zone, suggesting that air and water flow along the basal interface occurred and possibly was an active weathering zone. Analyses of samples from unweathered, unoxidized drill core samples and from the GHN rock pile are similar in clay mineralogy as determined by XRD and electron microprobe analyses, which suggests that the majority of clay minerals in the GHN samples were derived from the original, pre-mined hydrothermal alteration and not post-mining weathering.

Additional Key Words: mineral weathering, acid drainage, oxidation of rock piles, stability, mine waste rock

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ARD GEOCHEMISTRY IN THE DEVELOPING WORLD – DEALING WITH UNCERTAINTY, REGULATIONS AND THE NEED FOR CHARACTERIZATION OF MINE WASTE

Che McRae and Ken DeVos

Abstract. While many countries and international organizations have specific regulations for mining effluent and receiving water quality, the cause-and-effect link between mine wastes and the surrounding environment are often missed by regulators or mining companies. As a result, it is often the case that only limited data are available to decision makers at a time when it is most critical (e.g. project design and development phases). In an ideal world, the project would be delayed until sufficient data have been gathered to answer all pertinent questions. However, this is not always deemed feasible and therefore, decisions must be made with limited, often incomplete data sets due to aggressive scheduling and budgetary pressures. The decision making process is further complicated by regulations that are suitable for developed countries but may not be suitable for countries where socioeconomics, background chemical concentrations and artisanal mining are already causing significant human health impacts.

This paper will discuss decision-making in the face of uncertain data and will outline data requirements for the exploration stage that can reduce project delays and increase the confidence of particular decisions during project planning that are appropriate for the given, local conditions.
CHALLENGES IN USING LABORATORY-SCALE WASTE ROCK TESTING TO DEFINE THE GEOCHEMICAL BEHAVIOUR OF WASTE ROCK PILES

Che, McRae

Abstract. Laboratory-scale testing to characterize the acid rock drainage (ARD) and metal leaching (ML) properties of waste rock is routinely conducted to provide preliminary estimates of its potential environmental behaviour in disposal facilities. The laboratory-scale testing typically includes acid-base accounting, short-term leaching, elemental analysis, mineralogy and longer-term leaching to estimate kinetic behaviour. All of these tests are performed on small masses of rock that are collected to represent the compositional range and spatial distribution of the lithologies present, with consideration of the mass of waste rock excavated from a lithology.

Due to budgetary restrictions of the mining company or aggressive scheduling to obtain necessary permits, the initial laboratory-scale tests are sometimes all that are available to estimate the behaviour of the waste rock in the field. However, there are inherent differences between the laboratory-scale data and the field scale.

First, there is the sheer difference in scale. In the laboratory, sample masses are limited to less than 1 kg. In the field, waste rock piles can reach hundreds to millions of tonnes. While great care is taken to collect samples to properly represent the waste, the number of sample collected will in no way match the mass of waste rock to be extracted.

Second, laboratory tests are generally designed to enhance ARD and ML with small and uniform grain sizes. This results in enhanced oxidation rate and metal leaching. In the field, waste rock piles have a very broad range of particle sizes. While the finer fraction controls the bulk of the reactions, there is a large component of coarser grained rock that does not contribute as significantly. Therefore, when comparing reaction rates per unit rock mass, the lab tests and field test are not directly applicable and need to be corrected for the differences in the grain sizes.

Third, as the large waste rock piles grow in tonnage, they develop preferential flow pathways and unique hydrogeologies. This again limits the mass of rock that can contribute to ARD and ML. In the laboratory, this is not generally the case as all the tests are designed to effectively mix the rock and water.

To overcome these differences and to effectively use the laboratory data, correction factors can be used to account for the above. Alternatively, instead of loading rates based on mass, rates based on surface area may be used. The lab test results can be calibrated on small-scale field tests if available. In any of these cases, there is some component of reliance on professional judgment, other mining experiences and literature that is required to “make the leap” from lab to field.

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THE USE OF IN SITU MEASUREMENT OF HYDRAULIC CONDUCTIVITY TO PROVIDE AN UNDERSTANDING OF COVER SYSTEM PERFORMANCE OVER TIME\textsuperscript{1}

Greg P. Meiers, Lee S. Barbour, and Clara V. Qualizza\textsuperscript{2}

Abstract. Three prototype covers were constructed on a saline-sodic shale overburden fill at the Syncrude oil sands mine in Fort McMurray, Alberta, Canada in 1999. The covers are comprised of a surface layer of peat/mineral mix over glacial mineral soil placed over a sloping saline-sodic shale surface. The covers are designed to provide moisture storage for vegetation over the arid summer season while minimizing the impact of salt release from shale.

The evolution of the hydraulic performance of the covers was evaluated through repeated testing of \textit{in situ} hydraulic conductivity (K) over time. These changes are related to changes in monitored interflow collection rates. The mean K of the cover material increased approximately two orders of magnitude during the first three years following placement and then remained relatively constant. The interflow collection volumes have increased each year with the magnitude of interflow offset from the measured K values by two to three years. It appears that the interflow volumes which are critical for flushing salt from the covers are dependent on both the K of the cover and yearly climatic variability.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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SATURATED AND UNSATURATED HYDRAULIC PROPERTIES CHARACTERIZATION AT MINE FACILITIES: ARE WE DOING IT RIGHT1?

Michael A. Milczarek, Dirk van Zyl, Sheng Peng and Robert C. Rice2

The accurate determination of saturated and unsaturated hydraulic properties of mine waste and cover material is critical for predicting long-term drainage behavior and closure performance. The rock fragments typically found in mine waste and borrow materials complicate laboratory hydraulic property measurements. Many hydraulic testing laboratories address this issue by removing all material greater than 4.75 mm in diameter, repacking the remaining fine-earth sample in small diameter cores, and “correcting” the resulting measurements for the gravel content using published correction factors.

In order to evaluate several of the aforementioned gravel correction and hydraulic property prediction methods, a laboratory experiment was designed to test various well-graded gravelly materials. An alluvial material sample was used to fabricate eight soils with various particle size distributions. The primary sample matrix for all testing was chosen to be the fine-earth fraction, less than 4.75 mm in diameter. Additional soil materials were then fabricated in which either part of the fine-earth fraction was removed, or gravel material ranging from 4.75 mm to 19 mm diameter was added. Test results show that saturated hydraulic conductivity ($K_{\text{sat}}$) decreased with up to 30% gravel content but increased by orders of magnitude at higher gravel contents. Moisture retention characteristic (MRC) data showed that the air entry value decreased with increasing gravel contents, although the amount of retained water only slightly decreased as gravel content increased. Depending on how the MRC data is interpreted, the predicted unsaturated hydraulic conductivities either showed increasing hydraulic conductivity as gravel contents increased, or the values converge.

The measured hydraulic property data could not be accurately predicted using published correction factors, or by other prediction methods that use particle size distribution data. Consequently, removing the gravel fraction could result in significant error in the prediction of mine waste drainage behavior and the performance of cover systems. It is recommended that published correction factors not be used unless the sample is similar in gradation and bulk density to the soils tested by the published method. .

Additional Key Words: Moisture retention characteristic, gravel correction factor

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DESIGN AND CONSTRUCTION OF LIMESTONE BLENDED WASTE ROCK DUMPS - LESSONS LEARNED FROM A 10-YEAR STUDY AT GRASBERG

Stuart Miller, Yuni Rusdinar, Roger Smart, Judy Andrina and David Richards

Abstract. A ten-year acid rock drainage (ARD) mitigation program conducted by PT Freeport Indonesia at the Grasberg Mine, Papua Province, Indonesia has developed strategies to maximise the beneficial use of the mined limestone for ARD mitigation. Laboratory columns and field test pad investigations have examined limestone blends, layers and covers. Full-scale trial dumps comprising truck blends, conveyor/stacker blends and truck placed limestone covers have been constructed and monitored. Construction of an operational blended stacker built dump commenced in 2004 and is operated in accordance with blending specifications developed from the 10-year trial.

Trials have demonstrated that run-of mine truck constructed blended dumps are unlikely to be effective because the finer size fractions do not receive adequate limestone. Stacker-built dumps can be effective provided the blend ratio is based on achieving adequate acid neutralising capacity within the finer fractions.

Operational experience with the large stacker-built dump indicates that there is no discernable segregation of sulfur or acid neutralising capacity down the slope. The scheduling of potentially acid forming waste and limestone to the in-pit crushers is determining the spatial variability within the dump rather than segregation of sulfur or acid neutralising capacity during the dumping process.

Additional Key Words: blending, ARD, acid rock drainage, leach column, test pad, ANC, ANC/MPA ratio.

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MECHANISMS OF NICKEL AND ZINC REMOVAL IN OXIC LIMESTONE SYSTEMS AND THE APPLICATION TO METAL MINE DRAINAGES

Andy Miller², Linda Figueroa³, Tom Wildeman⁴

Abstract. Limestone systems are generally used for acid neutralization of mining impacted waters. However they can also be designed to remove heavy metal constituents. The issues surrounding the design of a limestone system for metal removal are different from the issues involved in acid neutralization. Experiments were carried out to explore these issues by evaluating the interaction of CaCO₃ with solutions containing a primary metal (Fe, Al), and a secondary metal (Zn, Ni). The fate of the secondary metals and their removal as a function of pH, alkalinity, and primary metal concentration are reported. Although these parameters by themselves are not necessarily good indicators of secondary metal removal, when coupled with the influent primary:secondary metal ratio, trends become apparent that can be used as design parameters. Zinc and Ni removals appear to be a function of Fe³⁺ concentrations and removals are shown to be as high as 97% and 87%, respectively, at near neutral pH values. The removal reaches a saturation point at an Fe:Zn ratio of 50:1, and for Ni the saturation ratio is 45:1. Zinc and Ni removals with Al gave ambiguous results.

Additional key words: co-precipitation, sorption, heavy metals, limestone drains

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LEACHATE AND ENZYME BIOASSAY TOXICITY ASSESSMENT TESTS AT THE TIP TOP MINE, A MARGINALLY IMPACTED SITE

Jessica Moehle, James Ranville, LaDonna Choate, Thomas Wildeman, and Philippe Ross

Abstract: Over the past three years, a decision tree has been developed to rank mine waste sites for potential environmental impacts. This approach relies on simple leach tests to determine the chemical composition and toxicity of water in contact with mining wastes. When the pH of the leachate solutions is less than 5, the toxicity of the water is certain. However, when the pH of the leachate solutions is greater than 5, lower concentrations of toxic metals make toxicity assessment uncertain and a simple “in-vitro” test is necessary. These methods were used to evaluate a mine site that is marginally impacted. The Tip Top Mine in Gamble Gulch, Colorado is a high mountain site where the stream upstream of the mine is pristine and downstream of the influx of acid rock drainage, the aquatic ecosystem is marginally impacted. Aquatic toxicity assessments, made using a microbial enzyme bioassay, were conducted to determine the impact of contaminants on the stream. All tests show that the stream water upstream of the adit inflow is unimpacted. However, the stream downstream of the inflow shows concentrations of Al, Cu and Zn that are only slightly higher than acute aquatic toxicity limits. Leaching tests on stream sediment samples taken at the adit entrance show concentrations of contaminants that are also higher than toxicity limits. Simple enzyme bioassay tests, using metals sensitive bacteria, were conducted to establish the toxic response of the sediment leachate. The preliminary results show that leachate water upstream of the adit is not toxic and downstream, the leachate solution is marginally toxic. Duplicate leach tests and enzyme bioassay tests were conducted to determine the reproducibility of these approaches.

Additional Key Words: enzyme bioassay, metal contamination, mine-wastes, contaminated soils and sediments, toxicity testing

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CASE STUDIES OF COSTS AND LONGEVITIES OF ALKALI-BASED WATER-TREATMENT PLANTS FOR ARD

Kevin A. Morin and Nora M. Hutt

Abstract. This paper provides an approach for roughly estimating the capital and annual operating costs, and the longevities (time to substantial replacement or upgrade), of alkali-based water-treatment plants for ARD. Under most combinations of flow and acidities, these plants will be the only cost-effective option for long-term consistent adherence to water-quality restrictions.

Median and mean capital costs were roughly US$3.8 and $4.5 million, and there was a correlation with average annual flow rate. There were no strong correlations among total annual operating costs, flows, and acidity concentrations due to highly variable individual contributions from factors like power and reagents. Nevertheless, an average unit-volume treatment cost was US$0.27/m$^3$ for acidities less than 800 mg/L, and was US$2.24/m$^3$ for acidities above 4000 mg/L.

The reported longevity of these water-treatment plants is around twenty years, attributable to factors such as increasing chemical loadings, increasing flows, and improved technology. A replacement period of 20 years can have a significant, but not dominant, effect on net present value over 100 years.

Passive treatment systems and soil covers do not usually attenuate concentrations consistently to non-toxic discharge levels, so additional treatment can be required. If this involves a water-treatment plant, an interplay of combined costs, longevities, durations, and risks leads to a myriad of waste-management scenarios. For example, a soil cover that lessens annual acidity loadings can extend the number of years a treatment plant operates; thereby increasing (1) the length of time the mining company must maintain a site presence and thus (2) the risk posed by a greater probability of intense storm events or other problems leading to an accidental release of contaminated water.

Long-term costs for passive treatment systems, like wetlands, and soil covers are not as well defined. This can give the false impression that water-treatment plants are more expensive in the long term.

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UPWARD MIGRATION OF CONSTITUENTS IN SOIL COVERS AT SEMI-ARID MINE SITES¹
Lewis Munk, Michael Jaworski, Michael Jojola, and Douglas Romig²

Abstract. Upward migration of either acidity or sodium is often cited as a concern when soil covers are placed over mine wastes. Regulatory concerns associated with upward migration are commonly used to justify capillary barriers or increased cover thickness. Upward migration of soluble salts is known to occur in soils with permanent or seasonal water tables near the soil surface and is a common problem in agricultural contexts. Short-term studies conducted at mine reclamation sites where changes in pH or salinity occurred at the contact between the soil cover and waste have been used to infer that upward migration would ultimately degrade cover quality. Thus, we investigated the potential for upward migration in soil covers overlying acid mill tailing and coal spoils 20 to 25 years after cover placement and revegetation. The soils were sampled and analyzed at discreet intervals above the soil-waste contact to assess upward migration. Changes in soil pH and/or extractable constituents were inconsistent among sites and varied from about 2 to 10 cm above the soil cover-waste contact. Field observations suggest that physical mixing of the cover and tailing during construction, rather than advection, accounted for acidification of the basal soil cover. Based on evidence from our investigations and an understanding of soil developmental processes in arid-regions, we conclude that upward migration of constituents from wastes is not a time-transgressive process that will result in cover degradation in arid and semi-arid regions where permanent or seasonal water tables occur well below the soil surface. Finally, we consider the changes in chemistry at the soil cover above the waste interface to be biologically insignificant.

Additional Key Words: Acid migration; soil covers; reclamation soil development; soil suitability.

¹Paper 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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APPLICATION OF RISK MANAGEMENT TO ABANDONED MINE SITES IN THE CANADIAN NORTH¹

Michael Nahir², Michael van Aanhout, Stefan Reinecke

Abstract. The Indian and Northern Affairs Canada (INAC) Northern Affairs Contaminated Sites Program (CSP) includes several large abandoned mine sites and is one of the largest contaminated sites programs in Canada. The program has developed a risk management procedure to provide a consistent methodology to evaluate the many types of risk at its sites, ensure that all high-risk items are identified, and provide a basis for prioritizing activities. This risk management procedure has been applied to nine abandoned mine sites. The high-risk scenarios identified for these sites were organized into common themes, or overarching issues. The five most common themes were: tailings impacts, health and safety risks due to public access, tenure issues, stored or spilled hazardous materials and petroleum hydrocarbons, and contracting issues. The most common consequences associated with high-risk scenarios within these themes were cost, health and safety, and community/media/reputation. The other types of consequences, including environmental impacts, legal obligations, and community/media/reputation, were not the main drivers for most of the high-risk scenarios. In addition to ongoing assessment and remediation activities at the abandoned mine sites, INAC is addressing the overarching issues identified by the risk management procedure through program-wide initiatives, including the development of new policies, guidelines, best practices and site-specific initiatives.

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PHYTOSTABILIZATION OF FLUVIAL TAILINGS DEPOSITS IN THE CLARK FORK RIVER FLOODPLAIN

Dennis R. Neuman & William M. Schafer

Abstract: Butte, Montana is the site of a world class copper deposit that has been mined nearly continuously since the 1870’s. Tailings deposits, a legacy of early mining practices, are abundant in the floodplain of the Clark Fork River, which has its headwaters near Butte. Tailings released by large-scale flooding in the early 1900’s form a patchwork in the floodplain. Waters that contact the pyrite-rich tailings are generally acidic and contain elevated copper, zinc, and arsenic levels.

Thinner tailings deposits (e.g. less than 15 cm) are fully oxidized and have become naturally re-vegetated. In areas with thicker tailings deposits, low pH (3 to 4.5) persists and tailings are devoid of vegetation. Evaporation from bare tailings concentrates metal sulfate salts at or near the surface. The bare tailings are susceptible to erosion and water flowing across the tailings dissolves metals and contributes metal loads to the Clark Fork River. In the middle and late 1980’s, large fish kills occurred in the Clark Fork after thunderstorms rinsed soluble metals, especially copper, into the river.

In 1990 and 1991, 4 km of the Clark Fork River near Warm Springs, Montana, was reclaimed using liming and both deep and conventional tillage techniques to reduce the mobility of metals in the floodplain and to allow re-establishment of vegetation. Successful stabilization of the floodplain soils has been amply demonstrated and phytostabilization was proposed as a cornerstone of the remediation efforts for the Clark Fork River superfund site. Environmental monitoring of the Clark Fork Demonstration project over a 14 year period is described in this paper.

Additional Key Words: Reclamation, ARD, metals, mining, Superfund, CERCLA

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MINERAL SOLUBILITY AND WEATHERING RATE CONSTRAINTS ON METAL CONCENTRATIONS IN GROUND WATERS OF MINERALIZED AREAS NEAR QUESTA, NEW MEXICO

D. Kirk Nordstrom and R. Blaine McCleskey

Abstract. The U.S. Geological Survey, in cooperation with the New Mexico Environment Department, has completed a 4-year investigation (2001-2005) to determine the pre-mining ground-water quality at Molycorp’s Questa molybdenum mine in northern New Mexico. Current mine-site ground waters are often contaminated with mine-waste leachates and no data exists on pre-mining ground-water quality so that pre-mining conditions must be inferred. Ground-water quality undisturbed by mining is often worse than New Mexico standards and data are needed to help establish closure requirements. The key to determining pre-mining conditions was to study the hydrogeochemistry of a proximal natural analog. Main rock types exposed to weathering include a Tertiary andesite and the Tertiary Amalia tuff (rhyolitic composition), both hydrothermally altered to various degrees. Two types of ground water are common in mineralized areas, acidic ground waters in alluvial debris fans with pH 3-4 and bedrock ground waters with pH 6-8. Siderite, ferrihydrite, rhodochrosite, amorphous to microcrystalline Al(OH)$_3$, calcite, gypsum, barite, and amorphous silica mineral solubilities control concentrations of Fe(II), Fe(III), Mn(II), Al, Ca, Ba, and SiO$_2$, depending on pH and solution composition. Concentrations at low pH are governed by element abundance and mineral weathering rates. Concentrations of Zn and Cd range from detection up to about 10 and 0.05 mg/L, respectively, and are derived primarily from sphalerite dissolution. Concentrations of Ni and Co range from detection up to 1 and 0.4 mg/L, respectively, and are derived primarily from pyrite dissolution. Concentrations of Ca and SO$_4^{2-}$ are derived from secondary gypsum dissolution and weathering of calcite and pyrite. Metal:sulfate concentration ratios are relatively constant for acidic waters, suggesting consistent weathering rates. These trends, combined with lithology, mineralogy, and mineral solubility controls, provide useful constraints on pre-mining ground-water quality for the mine site where the lithology is known.

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THREE COMPARATIVE EVALUATIONS OF TECHNOLOGIES FOR ELIMINATING ACID GENERATION FROM WASTE ROCK

Suzzann Nordwick, Norma Lewis, Diane Jordan, and Diana Bless

Abstract. MSE Technology Applications has independently evaluated several technologies for eliminating acid rock drainage (ARD) from waste rock, under the Mine Waste Technology Program. Summary information and results from three individual and separate demonstration projects will be presented. This paper is an extended abstract with only cursory project details and is meant to serve as an additional information source to the poster presentation material. The first project was a laboratory-based weather accelerated evaluation of two commercial technologies applied to unoxidized material. Evaluated over a two-year period were treatment technologies from Klean Earth Environmental Company (KEECO) and Metals Treatment Technologies (MT2). The second project was a field pilot-scale multi-cell evaluation of four technologies demonstrated at the Gilt Edge Mine Site. Treatment with lime was conducted along with treatment technologies from KEECO, University of Nevada, Reno (UNR), and MT2. The level of contaminants of concern released over time was monitored to determine technology performance, as the project objective was to reduce the effluent of each treatment cell effluent. The third project was a field-based demonstration with application to prevent acid generation on open-pit highwalls. Four technologies were applied at the Golden Sunlight Mine in Montana. Two treatment technologies, potassium permanganate and magnesium oxide, were from UNR. MT2 and Intermountain Polymers provided the third and fourth treatment technologies. The impact on total metals loading per unit area of each treated section was monitored. Results of the treatment effectiveness of the technologies tested in all three projects were obtained by comparison to control conditions by field monitoring and laboratory analysis. Results of the weather-accelerated project were most favorable to the KEECO technology. Results of the field multi-cell project were most favorable to the lime technology. Results from the highwall project indicated that all treatments reduced the concentrations of sulfate removed and reduced the mobility of metals from the highwall.

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2 Suzzann Nordwick, Senior Engineer, and Diane Jordan, Process Engineer, MSE Technology Applications, Inc., Mike Mansfield Advanced Technology Center, 200 Technology Way, P.O. Box 4078, Butte, Montana 59702, USA; and Norma Lewis and Diana Bless, United States Environmental Protection Agency, NRMRL, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, USA.
ADVANCES IN DEVELOPMENT OF BIOREACTORS APPLICABLE TO THE TREATMENT OF ARD

Suzzann Nordwick, Marek Zaluski, Brian Park, and Diana Bless

Abstract. Over the past 15 years, MSE Technology Applications has conducted several notable technology demonstrations of biologically based technologies to treat acid rock drainage (ARD). These projects have progressively evolved under the U.S. Environmental Protection Agency’s Mine Waste Technology Program (MWTP) and have resulted in significant advances in the development of bioreactor application of sulfate-reducing bacteria (SRB) technology. In this paper, summary information from four separate demonstration projects will be presented for the purpose of providing overviews of the bioreactor design parameters and the operation and development of each bioreactor system. Test methods and data analysis information for each project is not fully provided within this paper, as it is available from other sources. Summarized treatment results will be presented in this paper for three field-demonstrations. Additionally, results of one laboratory design project will be presented. A different bioreactor configuration was employed for each of the four projects. The first design to be presented will be an in situ bioreactor. This configuration was installed within the flooded subsurface workings of the Lilly Orphan Boy Mine in Montana and was operated between 1994 and 2005. The second design to be presented will be a set of on-site SRB bioreactors that were configured in parallel at the Calliope Mine in Montana. These test bioreactors allowed various operational attributes to be evaluated including lime pretreatment and temperature. The configuration of the third design to be presented will be a set of both anaerobic and aerobic bioreactors in staged fashion at the Surething Mine in Montana. This bioreactor design has been in operation since 2001 and shows the comprehensive applicability for biological treatment of ARD. The focus of the last project to be presented will be an investigative approach to bioreactor design. This resulted in a proposed bioreactor configuration to effectively treat ARD by reducing dissolved sulfate and heavy metals concentrations. In general, MWTP results from these four bioreactor configurations show that SRB bioreactors are effective for passive ARD treatment.

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CHOOSING REPRESENTATIVE CLIMATE YEARS FOR PREDICTING LONG-TERM PERFORMANCE OF MINE WASTE COVER SYSTEMS

M. O’Kane and S.L. Barbour

Abstract. An estimate of seepage from the footprint of a mine waste storage facility is required in order to evaluate potential impacts on the receiving environment. A soil cover system is often used in the design to reduce seepage and minimize meteoric water and/or oxygen from reaching the underlying waste. Typically, predicting cover system performance for use as input to seepage and groundwater models would involve modelling the annual “average”, “wettest”, and “driest” climate years on record.

This paper uses soil-atmosphere numerical modelling and cover system field performance monitoring from sites in the United States, Canada, and Australia to demonstrate that basing performance of a cover system on the annual average or extreme climate conditions alone can lead to inaccurate assessments of cover system performance. Sites with a variety of different climatic conditions are discussed including the impacts of snowmelt, fall and winter rainfall, and hot dry summers (with associated high intensity rainfall events).

It is found that net percolation rates predicted from the average annual precipitation record for a given site is typically not representative of the long-term average performance. The magnitude and occurrence of various precipitation events throughout the year, coupled with antecedent moisture conditions, plays a major role in actual net percolation rates through a cover system. Therefore, evaluating long-term average cover system performance using the average climate year may in fact result in a predicted net percolation rate that is not representative of the average net percolation. The long-term average performance of a cover system should be determined from a statistical analysis of the net percolation predicted for each year of the climate record. This methodology accounts for the impact of antecedent moisture conditions, as well as the occurrence and intensity of daily rainfall when determining the long-term average net percolation rate.

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TOWARD SOURCE CONTROL OF ACID ROCK DRAINAGE

Gregory J. Olson, Thomas R. Clark, Terry I. Mudder, Mark Logsdon

Abstract. Source control of acid rock drainage (ARD) requires consideration of both biological and abiotic mechanisms of metal sulfide oxidation. A promising approach is to couple a biocide with phosphate for application to sulfidic waste materials. This approach aims to 1) inhibit or kill with thiocyanate (SCN) the iron-oxidizing acidophilic microorganisms that accelerate sulfide oxidation and 2) precipitate FePO$_4$ and AlPO$_4$, thereby removing ferric ion oxidant and Lewis acidity, and, in the process, armoring the surface of pyrite to retard its abiotic oxidation. Thiocyanate effectively reduces sulfide biooxidation if it is applied efficiently and is not washed out of the system by rainfall or adsorbed to the rock. Several sources of phosphate including phosphate rock, waste material and agricultural products were characterized and tested in combination with SCN for their ability to retard oxidation of sulfidic waste rock. Waste rock sources include samples from base metal and precious metal mines and a coal mine. The acid neutralizing capacities (ANC) of different sources of phosphate were compared and evaluated using an artificial ARD solution which included iron and aluminum sulfates. Thiocyanate alone in laboratory tests sharply reduced ARD production, approaching the abiotic rate of sulfide oxidation. Whether thiocyanate plus phosphate further reduced ARD production depended on the mineral sulfide composition of the waste rock and the parameter measured. The abiotic sulfide oxidation rate of sphalerite-containing waste rock was reduced with phosphate treatment, most likely by removal of residual ferric iron from leach solutions. Phosphate did not further reduce abiotic sulfide oxidation rates with a pyritic waste rock, but did significantly reduce the soluble iron and other metal content of leachates. The combined thiocyanate plus phosphate treatment minimized biooxidation, removed ferric ion oxidant, and restricted formation of Lewis acidity but has not shown evidence of armoring pyrite. The laboratory test work guided the set up and operation of a 3000 t field test. ARD production was reduced over 50% in the first season with combined thiocyanate and phosphate treatment. However, washout of thiocyanate and its adsorption to rock reduced its concentrations in leachates to near zero in the second year of the test, greatly reducing the effectiveness of chemical treatment. Water soluble forms of thiocyanate (NaSCN) are best used to reduce ARD in situations where rainfall infiltration is low. The development of slow- or controlled-release thiocyanate products combined with phosphates would be beneficial.

Additional key words: ARD prevention, phosphate, thiocyanate

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2 Gregory J. Olson, Vice President, Thomas R. Clark, Senior Scientist, Little Bear Laboratories, Inc., Golden, CO 80403; Terry I. Mudder, Managing Director, TIMES, Ltd., Sheridan, WY 82801; Mark Logsdon, Principal Geochemist, Geochimica Inc., Aptos, CA 95003.
PREDICTING DEPTH TO SULFIDIC SEDIMENTS IN THE COASTAL PLAIN OF VIRGINIA

Zenah W. Orndorff, W. Lee Daniels

Abstract. Construction through sulfidic materials in the Coastal Plain province of Virginia has resulted in localized acid sulfate drainage that threatens water quality, fill stability, integrity of building materials, and vegetation management. Information regarding the likelihood of encountering sulfide-bearing sediments in construction zones can help minimize the negative impacts that result from the exposure of these materials. The objectives of this study were to evaluate field relationships between depth to sulfide-bearing sediments and landscape parameters, and to test models for predicting depth to sulfides. A study area in Hanover County, Virginia was evaluated using landscape parameters including elevation, slope, distance to streams, and surficial geology to predict depth to reduced sediments (depth-rs). Actual depth-rs values were interpreted from stratigraphic data for 408 well logs obtained from the Hanover County Health Department. A regression model could not be developed to accurately predict depth to sulfidic sediments based on the landscape parameters. Similarly, interpolation using a random subset of the well log data was unsuccessful at predicting depth-rs for the remaining points. However, since excavation depths in the study area are typically less than 9 m a procedure was developed to evaluate the likelihood of encountering sulfidic sediments within this depth based on two risk factors - elevation and soil type. This procedure accurately described the likelihood of encountering depth-rs within 9 m for 90% of 58 test points. Samples collected from twenty-three deep borings all had relatively high sulfur values and did not contain calcium carbonate, indicating that exposure of Tertiary sediments would always present a high risk of acid production.

Additional Key Words: acid rock drainage, acid sulfate soils, construction, pyrite, soil-landscape relationships
THE EFFECT OF WATER TABLE ELEVATION ON ACID MINE DRAINAGE FROM REACTIVE TAILINGS: A LABORATORY AND NUMERICAL MODELING STUDY\textsuperscript{1}

M. Ouangrawa\textsuperscript{2}, J. Molson\textsuperscript{2}, M. Aubertin\textsuperscript{2}, G. Zagury\textsuperscript{2}, and B. Bussière\textsuperscript{3}

Abstract. Laboratory column experiments and numerical simulations are used to evaluate the effectiveness of an elevated water table as a management and reclamation method for acid-generating mine tailings. The laboratory experiments involved monitoring oxygen and effluent chemistry from several columns of mine tailings with different water table elevations. Each column contained a layer of reactive tailings overlain by a sand cover and was subjected to transient recharge and flushing in fourteen 30-70 day cycles for 502 days. A free-draining control column with no sand cover was also used. The experimental results were compared with numerical simulations using the fully coupled reactive transport model MIN3P, which included infiltration, saturation-dependent oxygen diffusion, pyrite oxidation, multi-component geochemical reactions, and mineral buffering. The numerical results were consistent with the observed data which showed that an elevated water table can be very effective in reducing the production of acid mine drainage.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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Abstract. Grootvlei Mine is located in the Far East Rand Basin, part of the Witwatersrand Basin, which has been actively mined for over 100 years. In order to maintain access to its reserves, Grootvlei dewater approximately 75 ML/day from its workings. The water is treated and discharged to the Blesbokspruit.

A portion of the water pumped from underground is believed to originate from surface water. Technical assessments to identify the areas of ingress, quantities of ingress and possible measures to reduce the ingress are the subject of this paper. In addition, progress made with remediation works on one identified ingress area is discussed. The remedial works are being carried out by Grootvlei Mine, with partial funding provided by the Council for Geoscience.

The site represents a difficult working environment due to the very wet conditions resulting from historical roadway construction and tailings spills.
RECLAMATION AND CLOSURE OF SUMMER CAMP PIT LAKE, NEVADA: A CASE STUDY

Jeffery V. Parshley, Robert J. Bowell, and John Ackerman

Abstract. The Summer Camp Pit (SCP) is situated on the Placer Dome owned Getchell Property in Northern Nevada. The deposit is a typical Carlin type partly oxidized disseminated sulfide-micron gold deposit in strongly deformed and altered Paleozoic metasediments. The pit was mined by a former site owner from March 1990 to December 1991. Although the pit was mostly dry during operations, flows increased as mining deepened the pit, forcing the operators to begin periodic pumping of a small sump in the SW corner of the pit. A small sump developed which due to sulfide oxidation showed low pH and elevated metals and sulfate. To buffer this chemistry the pit was partly filled by water from the underground mining operations approximately 1 mile to the north of the pit and the water level maintained above the oxide-sulfide boundary.

The pit lake was monitored at the site for approximately 10 years and during this time the pit was used as part of the site water management strategy. For operational reasons, water was removed from the pit in 2002 and this resulted in exposure of sulfides in the pit wallrock, causing further oxidation and acid generation to occur. The chemistry of contact water created by exposure to these materials exhibited low pH with elevated metals and sulfate concentrations. Getchell Gold Corporation evaluated various options for closure of the pit. Draining and partial backfill provided the most suitable closure alternative for this pit, because it would eliminate the pit lake, reducing the potential for future groundwater impacts and risks to terrestrial and avian wildlife.

In order to evaluate the pit backfilling alternative, it was necessary to 1) identify appropriate and available backfill materials, and 2) ensure that those materials do not present an equal or greater risk to groundwater than the existing in-pit materials. The evaluation of potential backfill materials in the vicinity of SCP was based on environmental risk assessment, geochemical testwork and engineering considerations.

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SOURCE MANIPULATION IN WATER BODIES OF FLOODED UNDERGROUND MINES – EXPERIENCES FROM THE WISMUT REMEDIATION PROGRAM

Michael Paul, Ulf Jenk, Jürgen Meyer, Manfred Gengnagel

Abstract. Following reunification of Germany in 1990 the uranium production in eastern Germany (former GDR) was abandoned. Wismut GmbH was established as a federal company and put in charge of decommissioning and rehabilitating the uranium mining liabilities. The Wismut Remediation Program comprises the full scope of mine environmental remediation activities, i.e. remediation of underground and open pit mines, waste rock dumps, tailings ponds, area cleanup, decommissioning and demolition. As a crucial element of the closure plan the Wismut project includes the flooding of five underground mines which account, after groundwater rebound has been completed, for the bulk of contaminated waters to be treated at the different mine sites over the long-term. In order to optimize long-term water treatment and to minimize annual treatment costs, a set of alternative approaches to directly influence the contaminant loads to be handled at the surface has been investigated at different scales. As a result of these activities Wismut introduced a set of different methods of direct or indirect source manipulation of water bodies in flooded underground mines into the closure plans.

In the Königstein-ISL-mine an immobilisation technology, which is based on the injection of water supersaturated in barite into former leaching blocks has been implemented as part of the closure plan in order to immobilize parts of the contaminant potential. As an alternative a reactive barrier approach had also been tested within the mine, however, this technology did not prove to be feasible under the site specific conditions of the Königstein mine. With the intention to decrease the uranium concentration in mine waters a set of studies has been carried out where the addition of zero valent iron has been investigated as a tool to establish reducing conditions underground.

At the Pöhla mine site a full-scale field test had been applied to evaluate if natural attenuation processes in the mine water column can be enhanced by simple changes in the mine water management scheme. A water management approach is also the basic instrument at the Ronneburg mine site in order to limit the water treatment costs by plugging the mine which induces mine water stratification.

Additional Key Words: mine flooding, uranium mining, natural attenuation, water quality, water management

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PROPERTIES OF TREATMENT SLUDGE DURING SEDIMENTATION AND CONSOLIDATION TESTS

Lincar Pedroni, Jean-Baptiste Dromer, Michel Aubertin, Greg Kennedy

Abstract. Sedimentation and consolidation tests have been conducted on sludge produced from an acid mine drainage (AMD) treatment plant. The testing program involved the development of a new laboratory system, designed and constructed to assess the specific properties of low density slurry. During the instrumented large size column tests, the evolution of sedimentation and hydrodynamic consolidation was monitored with optical observation of the solid-liquid interface, evaluation of density $\rho$ with gamma ray sensors, and measurement of pore pressure $u$ using transducers. At the end of each test, physical and geotechnical properties of the resulting sludge were measured. In this paper, the authors will present a brief overview of the set up, followed by a presentation of new test results with the analysis using sedimentation-consolidation theories. The results presented here will be used in future analyses to evaluate the volume changes of AMD treatment sludge in storage basins.

Additional Key Words: AMD, large strain, mechanical properties.

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OXIDATIVE DISSOLUTION AT BASIC pH OF A PYRITE-RICH SLUDGE DOPED WITH FLY ASH

Rafael Pérez-López, Jordi Cama, José Miguel Nieto, Carlos Ayora

Abstract. A study of sulfur-rich sludge (71.6% pyrite) dissolution at alkaline conditions (pH ca. 9) was investigated using non-stirred and stirred flow-through experiments at room temperature (26 ± 1.2°C) and O₂ partial pressure of 0.20 atm. The dissolution rate of pyrite-rich sludge was calculated based on the S release (aqueous SO₄²⁻) at the steady-state. Results show that: (1) in the non-stirred reactor the sludge dissolution is practically nil as a result of a Fe-mineral coating on the pyritic grains; (2) In the stirred reactor, such a coating is not observed for 600 h, and the sludge dissolution rate is 6.05x10⁻¹¹ mol m⁻² s⁻¹.

The dissolution kinetics at alkaline pH of the pyrite-rich sludge was also studied adding a fly-ash material (residue of coal combustion) to the mining waste using saturated column experiments. It is observed that: (1) A leaching experiment with a fly-ash column and neutral pH eluent enhanced the neutralization capacity of this material, yielding a leachate pH of approx. 10; (2) In a saturated column, consisting of an initial thick layer of fly-ash material and a layer of pyritic sludge, attenuation of the pyrite-rich sludge oxidation is attained at pH approx. 10 due to Fe-mineral coating on the pyrite grains (e.g., pyrite encapsulation); (3) In a saturated column experiment solely filled with the pyritic sludge, oxidation occurred favourably at pH approx. 3.6.

Additional Key Words: oxidative, kinetics, pyrite, basic, pH.

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ACID NEUTRALIZATION AND METALS RETENTION IN SULFIDE-RICH MINING WASTES INDUCED BY THE ADDITION OF FLY ASH

Rafael Pérez-López, José Miguel Nieto, Gabriel R. Almodóvar

Abstract. In mining environments with sulfide-rich wastes, the aqueous oxidation of pyrite and other metallic sulfides (arsenopyrite, chalcopyrite, sphalerite, galena, etc.) originates an acid drainage with high contents of sulfate and metals called Acid Mine Drainage (AMD). In this work, the oxidative dissolution of a sulfide-rich sludge sample (71.6% pyrite) from the Iberian Pyrite Belt (IPB), the generation of acid mine drainage (AMD), and the potential use of fly ash (a residue of coal combustion) to neutralize the acidity and reduce the metal content of the drainage, have been studied in column experiments.

Obtained results show that: (1) a non-saturated column experiment filled with pyrite-rich sludge with artificial irrigation leached an acid drainage (pH approx. 2) with high concentrations of sulfate, iron and heavy metals; (2) non-saturated columns filled with sulfide sludge and fly ash leached a drainage characterized by high pH values (pH ≈ 10), very low sulfate content, and lack of iron and other metals in solution; (3) inside columns with fly ash, the pyrite oxidative dissolution at high pH (as a consequence of the leaching of fly ash) favours metals precipitation (mainly iron), the coating of pyrite grains and the oxidation attenuation; (4) in addition to ferric hydroxide coating, the precipitation of other minerals in the interface between pyrite-rich sludge and fly ash developed a rigid crust, or hardpan, which isolates mining waste from the weathering processes.

Definitely, the addition of fly ash to a pyrite-rich sludge showed an improvement of the quality of the acid drainages and the development of mechanisms (iron coating and hardpan formation) that prevent the AMD production in a long term.

Additional Key Words: acid, metals, neutralization, sulfide-rich wastes, fly ash.

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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WATER QUALITY EVOLUTION IN FLOODED AND UNFLOODED COAL MINE-POOLS\textsuperscript{1}

Eric F. Perry\textsuperscript{2} and Henry W. Rauch

Abstract: Water quality and flow data from a pumped, mostly flooded, and a free draining, mostly unflooded coal mine-pools were analyzed for temporal trends. Both mine-pools began discharging acidic drainage, with pH < 3, iron (Fe) concentrations of 200 to > 900 mg/L, and sulfate (SO\textsubscript{4}\textsuperscript{2-}) values of about 2,500 to 4,000 mg/L, less than one year after closure. Each site had an initial flushing period, lasting about 2 years in the unflooded mine, and 8 years in the flooded mine. The flushing included a rapid decline in concentrations, and large variations in water chemistry. Chemical concentrations declined more rapidly in the flooded mine-pool, to about 20 to 30% of the initial values for Fe and SO\textsubscript{4}\textsuperscript{2-}. In contrast, after initial flushing, water from the unflooded mine had Fe, SO\textsubscript{4}\textsuperscript{2-}, and aluminum (Al) concentrations of 50 to 75% of original discharge quality.

Each mine-pool is now in a maturation process with continuing declines in chemical concentrations, less variation in composition, and increasing metals attenuation in the mine-pool aquifer. The flooded mine-pool turned net alkaline after pumping about 21 pool volumes. After 35 years, Fe and SO\textsubscript{4} are 5 to 10% of initial composition. Equilibrium calculations show that Fe may be controlled by poorly crystalline oxyhydroxides. Mine-pool oxidation reduction potential (ORP) is < +250 mv. The free draining mine still has pH < 3 after discharging about 25 pool volumes. Iron and SO\textsubscript{4} concentrations are still 25 to 40% of original composition and Al is unchanged since the initial flush. Equilibrium calculations show that Fe may be controlled by oxyhydroxides or K-jarosite. Mine-pool ORP is +500 to 700 mv. Al is near apparent equilibrium with jurbanite. Declining Fe to SO\textsubscript{4}\textsuperscript{2-} ratios in both mine-pools indicate that 60 to 80% of Fe dissolved from pyrite is being attenuated in-situ, probably by precipitation, exchange or adsorption.

Flooding has suppressed, but not eliminated pyrite oxidation in one mine-pool. The free draining mine water chemistry is still controlled by sulfide oxidation. Both mine-pools may contain dissolved Fe from continuing mineral dissolution in the mine-pool aquifer indefinitely.

\textsuperscript{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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GEOCHEMICAL CHARACTERIZATION OF MINE WASTE FROM THE
PIKE HILL SUPERFUND SITE IN VERMONT, USA

Nadine M. Piatak, Jane M. Hammarstrom, and Robert. R. Seal II

Abstract. The Pike Hill mines Superfund site consists of a group of mines that worked copper-rich Besshi-type massive sulfide deposits. The site contains the abandoned Smith, Eureka, and Union mines and was listed in 2004 as a Superfund site due to aquatic ecosystem impacts. This study is part of a larger project that includes mine waste characterization, surface-water geochemical studies, and documentation of downstream impacts on biota. It is intended to be a precursor to a formal remedial investigation by the U.S. Environmental Protection Agency (USEPA). The goal of this paper is to provide a relative comparison of the various waste piles through characterization of bulk geochemistry, mineralogy, paste pH, acid-base accounting, and metal leachability. In addition, results were compared to similar studies of mine waste from the nearby Ely and Elizabeth Superfund sites. Mine-waste samples at the Pike Hill mines include flotation-mill tailings and waste rock that is composed of fine-grained to boulder-sized host rock and mineralized rock. The waste is primarily composed of silicates, oxides, sulfates, and sulfides, including pyrrhotite, pyrite, chalcopyrite, and sphalerite. Samples locally contain native sulfur and calcite; efflorescent sulfate salts have been observed on waste piles and adit walls. Composite mine-waste samples contain concentrations of Cd, Cu, and Fe that exceed USEPA Preliminary Remediation Goals (PRGs). The concentrations of Se are elevated relative to the average composition of eastern U.S. soils. All mine-waste samples, except the processed flotation-mill tailings, which contain calcite, have paste pH values of 4 or less and negative net-neutralization potentials indicating the samples are acid generating. Twenty-four-hour leachate tests, which use a solution that approximates eastern U.S. precipitation, indicate that potentially toxic trace elements and acidity can be released under simulated weathering conditions. Mine waste at Pike Hill mines is chemically and mineralogically similar to that at the Elizabeth and Ely mines. Also, metals are leached and acid produced in comparable concentrations. Based on the results of this study, mine waste at the Pike Hill Superfund site contaminates soils, is acid generating, and may release potentially toxic metals to streams.

Additional Key Words: cadmium, copper, leachate, massive sulfide, metals, sulfides, Superfund, tailings, toxicity, zinc.

Poster 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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ACID MINE DRAINAGE IN CZECH REPUBLIC – LEGAL REGULATIONS, POLLUTION, MANAGEMENT

Vaclav Pisa, Eva Gulikova

Abstract: Brown coal is a significant raw material for power in the Czech Republic. At present each year approximately 50 millions tons of brown coal is mined and almost the whole quantity is used for power purposes. Brown coal is currently mined only at opencast mines in two areas situated in the western part of the Czech Republic. Every year around 12 million m³ mining waters (AMD) are drained to the drainage canals.

Brown coal and the overlying materials in some localities have an increased content of sulfur (2 – 8%; largely as pyrite) and of course it is an important contributor to pollution by AMD.

Characteristic AMD from brown coal opencast mines (Table 1):

Table 1

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>LONG-TIME VALUES</th>
<th>EXTREME VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5 - 9</td>
<td>2.5</td>
</tr>
<tr>
<td>SO₄²⁻ (mg/L)</td>
<td>400 – 2 500</td>
<td>&gt; 5 000</td>
</tr>
<tr>
<td>Fe₉tot. (mg/L)</td>
<td>&lt; 0,1 – 30</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>Mn (mg/L)</td>
<td>&lt; 0,1 – 5</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>Undissolved Solids (mg/L)</td>
<td>&lt; 5 – 200</td>
<td>&gt; 10 000</td>
</tr>
<tr>
<td>Dissolved Solids (mg/L)</td>
<td>800 – 3 000</td>
<td>&gt; 6 000</td>
</tr>
<tr>
<td>PAH *) (mg/L)</td>
<td>&lt; 10⁻⁵ – 10⁻⁴</td>
<td>10⁻³</td>
</tr>
</tbody>
</table>

*) PAH (a total of 6 compounds – Fluoranthene, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[a]pyrene, Benzo[ghi]perylene, Indeno[1,2,3-cd]pyrene)
***) Effect of geological conditions, no climatic cond.

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CHARACTERIZING AND TRACKING REACTIVE MIXTURE ALTERATIONS: NEW TOOLS FOR PASSIVE TREATMENT SYSTEM DESIGN AND MONITORING

Daphne L. Place

Abstract. Microorganisms within passive reactive zones (e.g. wetlands, SR bioreactors, PRB’s, etc.) utilize organic substrates in the process of reducing sulfate and immobilizing metals in mine drainage waters. The rate and extent of substrate utilization influences treatment longevity and performance. Tracking substrate utilization is a quantitative tool for planning and design, accomplished by characterizing alterations in reactive mixtures temporally and/or spatially. Characterizing alterations is applicable to selecting substrates, developing microbial utilization rates and rate curves over time, and assessing temporal and spatial variations within treatment zones. The characterization of alterations is determined using a method adapted from a sequential extraction technique used to determine carbohydrate and lignin composition in agricultural products. This paper presents the results of an evaluation of alterations in the reactive mixture composition of two bench-scale bioreactors and a field-scale passive treatment system. Interpretation of these results supports the use and applicability of characterizing and tracking alterations as a new tool for designing and monitoring passive treatment systems. The four selection criteria for determining the appropriate reactive mixture to use in the system are: total organic, cellulose content, lignin content and cellulose to lignin ratio. Using total carbon to predict the longevity of passive treatment systems is insufficient because it does not detail if the carbon is in a bioavailable form for the microbial community. Interpretation of the results from these bioreactors shows how tracking substrate alterations over time can provide information on microbial utilization rates and generate rate curves. This paper evaluates the application of tracking substrate alterations at various locations within a field-scale passive treatment system, and describes how microbial utilization of organic substrate varies spatially. These results suggest that spatial tracking provides valuable insight for the monitoring of passive reactive treatment zones, thereby helping manage the sustainability of the passive treatment system by indicating when the reactive mixture needs to be refreshed.

Additional Key Words: bioreactors, field—scale systems, passive reactive barriers (PRBs), passive reactive zones (PRZ), Peerless Jenny King, performance and monitoring, reactive mixtures, remediation, sulfate reducing bacteria (SRB), sulfate reducing bioreactors (SRBR), substrate utilization, sustainability, treatment, wetlands.

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MICROBIOLOGY OF SULFATE-REDUCING PASSIVE TREATMENT SYSTEMS

Amy Pruden, Luciana P. Pereyra, Sage R. Hiibel, Laura Y. Inman, Nella Kashani, Kenneth F. Reardon, and David Reisman

Little is known about the microbiology of passive mine drainage treatment systems, such as sulfate-reducing permeable reactive zones (SR-PRZs). We have recently developed a suite of molecular biology tools in our laboratory for characterizing the microbial communities present in SR-PRZs. In this study our suite of tools is used to characterize two different field bioreactors: Peerless Jenny King and Luttrell. Both bioreactors are located near the Ten Mile Creek Basin near Helena, MT, and both employ a compost-based substrate to promote the growth of sulfate-reducing bacteria (SRB) for production of sulfides and precipitation of metals. In summer, 2005, the reactors were sampled at multiple locations and with depth. DNA was extracted from the compost material and followed by cloning of polymerase chain reaction (PCR) amplified 16S rRNA genes, restriction digest screening, and DNA sequencing to provide insight into the overall composition of the microbial communities. To directly examine the SRB populations, a gene specific to SRB, *apsA*, was PCR-amplified, cloned, and sequenced. This revealed that *Desulfovibrio* spp. were prevalent in both Luttrell and Peerless Jenny King. At Peerless Jenny King, one *Desulfovibrio* spp. found was noted to be particularly aerotolerant. This analysis also revealed that *Thiobacillus denitrificans* were common at Peerless Jenny King. This is an organism that oxidizes sulfides in the presence of nitrate, which is undesirable for biozone function. In order to quantify SRB, quantitative real-time PCR (Q-PCR) was used targeting two specific groups of SRB, *Desulfovibrio* and *Desulfobacteria*. These results indicated that these two SRB groups, which have distinct substrate requirements, vary in distribution between the two bioreactors and with depth. It is hoped that an improved understanding of the microbiology of these systems will help to improve design and operation of passive treatment systems employing sulfate reduction.

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DEVELOPMENT AND OPERATION OF A WATER BALANCE AT RIO PARACATU MINERAÇÃO, BRAZIL

Tobias Puhlmann\textsuperscript{2}, Charles Voss\textsuperscript{3}, Juliana Esper\textsuperscript{4}, Rodrigo Dutra Amaral\textsuperscript{2}

Abstract: RPM (Rio Paracatu Mineração) is evaluating several expansion alternatives that challenge the capacity of the current water supply system. Therefore, a site wide water model was developed to a) evaluate ways to optimise the operation of the existing water management system and b) evaluate alternative water infrastructure and water supply options that would meet the requirements of future mine expansions.

The water model was developed using a probabilistic dynamic system modelling platform. System simulation models provide a framework for organising the components, processes and operations at a mine and then explore the existing and alternative approaches to gain a diagnostic understanding of the mine system. The process of developing a system model provides a basis for sharing and documenting specialised knowledge, expertise, experience and priorities within the mining operation.

After developing a conceptual model the dynamic system modelling platform was used to produce a mathematical representation of the water management relationships. The model was then calibrated and validated before using it for optimisation and planning exercises.

The model development process has resulted in better documentation of the current water management operations and an improved understanding of the system components. This holistic view of water resourcing from freshwater withdrawal to tailings discharge as well as a convenient platform for performing “what if” experiments is facilitating ongoing improvements in water management at RPM. The model provided useful risk-based projections to assess the feasibility of expanding mine production from 20 to 30 million tonnes per year.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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INTEGRATING BIOAVAILABILITY APPROACHES INTO WASTE ROCK EVALUATIONS

James Ranville\(^2\), Eric Blumenstein, Marty Adams, LaDonna Choate, Kathleen Smith, and Thomas Wildeman

**Abstract:** The presence of toxic metals in soils affected by mining, industry, agriculture and urbanization, presents problems to human health, the establishment and maintenance of plant and animal habitats, and the rehabilitation of affected areas. A key to managing these problems is predicting the fraction of metal in a given soil that will be biologically labile, and potentially harmful (‘bioavailable’). The molecular form of metals and metalloids, particularly the uncomplexed (free) form, controls their bioavailability and toxicity in solution. One computational approach for determining bioavailability, the biotic ligand model (BLM), takes into account not only metal complexation by ligands in solution, but also competitive binding of hardness cations (\(\text{Ca}^{2+}, \text{Mg}^{2+}\)) and metal ions to biological receptor sites. The more direct approach to assess bioavailability is to explicitly measure the response of an organism to a contaminant. A number of microbial enzyme tests have been developed to assess the impact of pollution in a rapid and procedurally simple way. These different approaches in making bioavailability predictions may have value in setting land-use priorities, remediation goals, and habitat reclamation strategies.

**Additional Key Words:** enzyme bioassay, biotic ligand model, metal contamination, mine wastes, contaminated soils and sediments, toxicity testing

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\(^1\) Paper presented at the 7\(^{th}\) 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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DESIGN AND IMPLEMENTATION OF A STRATEGIC REVIEW OF ARD RISK IN RIO TINTO


Abstract. Following an internal review of significant environmental risks in 2003, Rio Tinto developed, using a combination of in-house and external expertise, an ARD screening protocol to rank innate hazards at its mines and a second protocol to assess performance in key management areas during site-based risk reviews. Eight risk reviews were conducted in 2004 and another four in early 2005, at mines covering a wide range of commodities, operating methods and project stages. These reviews have proven successful in identifying and reducing ARD-related risks within Rio Tinto. Site-specific findings identified by these reviews are reported through corporate assurance processes with progress on agreed remedial actions being tracked semi-annually. Some common issues, covering aspects such as characterisation, groundwater monitoring and modelling, material segregation, cover design and flooding of workings, were identified at multiple sites. These have also been addressed by strengthening existing corporate environmental standards and guidance for ARD prediction and management. This paper summarizes the methodologies and the major findings of the first two years of the Rio Tinto program.

1 Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502
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REACTIVE TRANSPORT MODELING OF AMD RELEASE AND ATTENUATION AT THE FAULT LAKE TAILINGS AREA, FALCONBRIDGE, ONTARIO

Connie G. Romano, K. Ulrich Mayer, and David W. Blowes

Abstract. Numerical simulations of the Fault Lake Tailings were conducted to assess the long-term impact of AMD-generation on downgradient receptors. The effects of impoundment geometry, contrasting permeability, water content, and mineralogy of tailings and native sediments were considered. Simulation results suggest that over a time period of 1,000 years only the top three meters of tailings become oxidized and that AMD is preferentially released at the periphery of the impoundment. Although the permeability of the tailings is lower than that of the aquifer and groundwater flow is deflected around the deep saturated tailings mass, AMD is not inhibited from percolating into the aquifer, because the bulk of the tailings are located within the vadose zone. The carbonate content of the underlying material likely provides sufficient buffering capacity to attenuate most metals and neutralize pH over the long-term.

Additional Key Words: sulfide mineral oxidation, porous envelope effect, mass loading, sensitive receptor

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LEAF AREA AND ROOT DENSITY MEASUREMENTS FOR USE IN COVERAGE PERFORMANCE EVALUATIONS ON SEMI-ARID RECLAIMED MINE LANDS

Douglas Romig, Lewis Munk, and Todd Stein

Abstract. Evapotranspiration (store and release) soil covers have been proposed as a means to limit acid mine drainage. Soil water balance models, like UNSAT-H are commonly used to assess the effectiveness of store and release covers. Plant-related attributes are required as inputs to these models. In particular, UNSAT-H requires leaf area index (LAI) and root length density (RLD) inputs. Published LAI and RLD data are generally lacking for semi-arid plant communities. To resolve this data gap, we collected leaf area and root density measurements in native and reclaimed shrub-grassland communities in southwestern New Mexico. Leaf area indices were determined using digital image analysis of harvested leaves at the end of the growing season. These data were used to estimate peak LAI and develop an annual LAI distribution. The average LAI ranged from 0.29 in reclaimed plant communities to 0.42 in native shrub-grasslands. LAI values for the reclaimed site did not correspond to soil cover thickness, which ranged from 23 to 62 cm. However, higher LAI values were typically associated with plots with higher amounts of shrub cover. Preceding drought and heavy grazing probably affected the LAI data in both native and reclaimed areas. Root density was measured in soil excavations using a grid-count method. Root density measurements indicated that nearly two-thirds of the roots occurred in the upper 20 cm of the soil in both the reclaimed and native areas. Very few roots occurred below 1.0 m. RLD was described by the quartile function 69-20-7-4 in the upper meter of soil. Preliminary water balance simulations using a 100-year climate record indicate that average drainage was less than 1 percent of mean annual precipitation when the measured LAI and RLD functions were applied to a 60 cm thick cover.

Additional Key Words: leaf area index, root length density, soil cover, soil water balance model, UNSAT-H

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LONG-TERM PERFORMANCE OF VERTICAL FLOW PONDS – AN UPDATE$^1$

Arthur W. Rose$^2$

Abstract. Some vertical flow ponds (VFP’s, SAPS) are performing less well than expected. This paper compiles quantitative data on performance and problems to extend previous evaluations in 2002 and 2004.

Of 40 sites, about half are performing entirely satisfactorily. Six sites have essentially ceased to treat. Most of the remainder are treating at a moderate level, but not up to original expectations, which in some cases were unrealistic. Problems include overflow because of plugging by Fe precipitate on top of compost or by Al precipitate in limestone, leakage, decreased treatment because of short-circuiting or Al coating, or inadequate size for the acidity loading. Low-cost rebuilding has restored several systems. Some problems result from inadequate preconstruction flow and chemical data.

The evaluation shows that vertical flow ponds are an effective method for treatment of most net-acid discharges if the ponds are properly designed and constructed. Improved designs such as bioreactors or automatic flushers may be needed for systems with influent Al exceeding about 20 mg/L.

Additional key words: Passive treatment, acid mine drainage, coal mine drainage, SAPS, economics.

$^1$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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GEOSTATISTICAL MODELING OF ACID ROCK PREDICTION
UNCERTAINTY

Mario E. Rossi

Abstract. The estimation of actual or potential acid rock drainage (ARD) at mine sites is usually accomplished by sampling specific parameters that allow detection and prediction of the potential for ARD. The use of block models to estimate and describe the spatial extent of relevant variables is becoming more common, although quantification of the uncertainty associated with the problem is generally not available, yet it can be critical in an ARD characterization study.

Uncertainties in sampling and analytical processes, in the characterization of the volumes and areas affected or potentially affected by ARD, in the interpolation of sampled values, and in the characterization of physical processes that allow prediction of fate and transport, are always present. It is unrealistic to pretend that the estimation process is error-free, and thus it follows that it is important to provide adequate models of uncertainty, in addition to reasonable estimates of ARD potential. The model of uncertainty can then be used to develop technical risk assessments, including false positives or negatives of certain variables exceeding (or not) certain thresholds.

This paper outlines a stochastic method based on geostatistical conditional simulations that allows assessment and modeling of uncertainty in spatial modeling. This assessment is then translated into risk levels, allowing for a decision-making process that is based on levels of uncertainty. The concept of Loss Functions is illustrated with an example drawn from a porphyry Cu-Mo deposit in South America.

Additional Keywords: Acid Rock Drainage, Conditional Simulations, Uncertainty Model, Loss Functions, False Positives, False Negatives, Risk Models.

1Paper 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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EFFECTIVE PASSIVE TREATMENT OF MINE EFFlUENT USING A PHOSPHATE REACTIVE MEDIUM

Cheryl S. Ross, Rens B. Verburg, Bryony Stasney and Lynn McCloskey

Abstract. The Nevada Stewart Mine is an abandoned lead-zinc mine located within the Coeur d’Alene Mining District, Idaho. In 2002, a passive Apatite II\textsuperscript{TM} Treatment System (ATS) was installed by MSE Technology Applications, Inc. (MSE) to treat metal-laden adit discharge (pH values are circum-neutral). The treatment medium consisted of a mixture of fish bone (Apatite II\textsuperscript{TM}) and gravel.

Monthly performance monitoring of the ATS over a 21-month period showed attenuation of cadmium, lead, zinc, iron and manganese. In comparison to the ATS inflow, redox conditions in the outflow were more reduced, with higher calcium, sulfide, nitrogen and phosphorus concentrations. Geochemical modeling using the United States Geological Survey code PHREEQC was conducted to identify the reaction mechanisms responsible for the observed changes in water quality. Modeling results were reviewed in the context of available solid-phase data (i.e., chemical composition and detailed mineralogy) and experience at other sites to identify the most likely attenuation mechanisms. Zinc attenuation was attributed to precipitation as zinc sulfide, subsequently confirmed by mineralogical analysis. Collagen was identified as the most likely source of nitrogen release from the ATS, and was likely responsible for reducing conditions in the effluent. The increase in phosphorus concentrations was attributed to dissolution of the Apatite II\textsuperscript{TM} and subsequent formation of insoluble metal phosphates. Manganese phosphate [MnHPO\textsubscript{4}] and chloropyromorphite [Pb\textsubscript{10}(PO\textsubscript{4})\textsubscript{6}Cl\textsubscript{2}] were identified as possible controls on manganese and lead concentrations, respectively.

Additional Key Words: Apatite II\textsuperscript{TM}, manganese, lead, zinc, PHREEQC, geochemical modeling

\textsuperscript{1} Paper presented at the 7\textsuperscript{th} 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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CHALLENGES OF PASSIVE TREATMENT OF METAL MINE DRAINAGE IN THE IBERIAN PYRITE BELT (SOUTHERN SPAIN): PRELIMINARY STUDIES

Tobias S. Rötting, Robert C. Thomas, Carlos Ayora, Jesus Carrera

Abstract. AMD in the Iberian Pyrite Belt is a problem of global scale. Successful implementation of passive treatment systems could remediate at least part of this problem at reasonable costs. However, initial trials with ALD and RAPS based on gravel size limestone failed due to rapid loss of chemical reactivity and plugging. Limestone buffered organic substrate (LBOS), which employs fine-grained limestone in an organic matrix, is an attractive alternative to conventional RAPS or ALD substrates, because it combines high reactivity with low plugging. However, LBOS has only been tested on ferric-iron waters, while our target AMD is mainly ferrous-iron. Due to the high ferrous to ferric iron ratio, we envision a LBOS treatment system that relies on sulfate reducing bacteria (SRB) in addition to the fine-grained limestone in the substrate. This study presents preliminary batch and column trials on reactivity and hydraulic properties. Other challenges include finding appropriate and locally available LBOS components. Tested substrates include compost, wood chips, limestone screenings and sugar beet lime.

Results show that only some SRB types tolerate the high metal concentrations. Reactors with SRB activity produce higher alkalinity, but support lower flow rates than reactors based on limestone dissolution only.

Additional Key Words: Limestone buffered organic substrate, LBOS, plugging, armoring.

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GROWTH INHIBITION OF CELLULOMONAS FLAVIGENA INDUCED BY COPPER AND ZINC: DETERMINATION OF TOXICITY THRESHOLDS AND THE COMBINED EFFECTS OF COPPER AND ZINC ON THE GROWTH OF A CELLULOLYTIC-FERMENTING BACTERIA

A. Ruhs, L. Figueroa and T. R. Wildeman

Extended Abstract: The effective use of anaerobic passive treatment systems (APTS), such as sulfate-reducing bioreactors, to treat acid mine drainage will help to mitigate water contamination from mines located in remote areas as well as cut current treatment costs. One drawback to APTS has been an observed decline in long-term performance. Several environmental factors, such as initial metals concentration and temperature, may contribute to observed declines in sulfate reduction carried out by the microorganisms. APTS contain a complex microbial ecosystem, and metal toxicity could be indirectly affecting sulfate-reduction by inhibiting other important microbes. Previous research has found that organisms capable of degrading cellulose (cellulolytic-fermenters) are dominant within a sulfate reducing bioreactor (Pruden et al., 2005), and their ability to produce viable substrates for the sulfate-reducing bacteria is the rate-limiting step in sulfate reduction (Logan, 2003). This investigation examines the individual effect of zinc and copper, and then the combination of both metals, on a pure culture of cellulolytic fermenters, specifically Cellulomonas flavigena (ATCC 482).

C. flavigena exhibited 50% growth inhibition between a copper concentration of 0.00188 mM and 0.0038 mM. Further investigation of growth inhibition within this range of copper concentrations is currently underway. Glucose consumption was also much less in the copper containing bottles, as expected due to the low biomass observed in these bottles. The pH remained relatively constant throughout the experiments, staying within an optimal microbial growth range between pH 6 and 7. Possible changes in solution phase metals concentration and organic acid production throughout the experiments were monitored, and these results will be available during the ICARD conference. Concentrations of Zn(II) at 0, 0.125, 0.25 and 0.5 mM were also examined to determine the effects on cell growth for C. flavigena. The results for zinc toxicity and a binary metal mixture will be presented at the 2006 ICARD conference.

Additional Key Words: Anaerobic Passive Treatment System, sulfate reducing bioreactor

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LONG TERM ACID ROCK DRAINAGE (ARD) MANAGEMENT AT PT FREEPORT INDONESIA

Yuni Rusdinar

Abstract. Freeport Indonesia currently operates a 760,000 t/d open pit mine that will operate until 2015, with the resulting placement of approximately 2,750 Mt of overburden rock.

Laboratory column tests, 500-tonne test pads, and industrial-scale dump trials have been highly successful in gaining an understanding of ARD evolution, metal release kinetics, and the development of key design specifications for long-term ARD control through limestone blending and limestone covers at the Grasberg Open Pit Mine.

Ongoing work will focus on evaluating and monitoring the effectiveness of limestone blending and limestone covers as an integral part of life-of-mine overburden management practices.

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Abstract. Scientists, mining companies, and governments are trying to ameliorate the environmental effects of acid rock drainage (ARD), and abandoned mines, and to address sustainability issues to the mining community nationally and internationally. Failures to adequately address mine drainage issues have occurred at relatively high rates over the past several years. Many of these failures have resulted in massive damage (both real and perceived); with severe economic impact to both taxpayers and companies. This personal summary of lessons learned of mine sites from A to Z has been compiled to identify commonalities and to illustrate the primary issues encountered when dealing with mining influenced waters. Clear trends regarding the need for good baseline information, development of innovative technologies and common issues arise from objectively reviewing a multitude of case histories. Understanding these trends greatly assists in enhancing current and future design, construction, operation, and closure of mining facilities. Ignorance of past failures can be overcome by lessons learned thus contributing to the knowledge base and avoiding similar problems in the future.

Additional Key Words: abandoned mines, environmental protection agency, mine monitoring, prediction, water balance, water treatment, historic mines, lessons learned

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2 Carol Cox Russell, Acting Chief Water Quality Unit, U.S. Environmental Protection Agency 999 18th Street suite 300, Denver, CO 80202
Abstract. Selected results of an international review of soil cover design and construction practices and performance is presented in this paper. The review, which was carried out in 2003, initially included 177 case studies in 14 countries. This has subsequently been updated to include more than 200 individual case studies. The case studies include soil covers for tailings impoundments, waste rock piles, backfilled pits and heap leach pads. The mining operations included precious metals, uranium, coal and oil sands. This is the first international review to focus on the practical questions related to soil cover construction practices, and specifically how that relates to long-term cover performance. This paper provides some suggestions as to how operators, regulators and practitioners could improve soil cover design and construction practices, as learned from these actual case studies.
ARSENIC IN OXIDATION PRODUCTS OF HIGH SULFIDE, REFRACTORY ARESENOPYRITE MINE WASTE, SNOW LAKE, MANITOBA, CANADA

K.A. Salzsauler, B. L. Sherriff, and N. V. Sidenko

Abstract: Between 1948 and 1959, 250 000 tonnes of cyanide treated, high sulfide refractory ore concentrate were stored in a waste rock impoundment at Nor-Acme Mine, Snow Lake, Manitoba, Canada. Over 40 years of exposure resulted in the development of a supergene alteration profile in the waste. The pile was capped with layers of waste rock, clay and silt in 2000 to prevent water infiltration and the oxidative release of arsenic.

The primary sulfide mineralogy of the residue was 55% arsenopyrite, 10% pyrrhotite, and 5% pyrite. Prolonged exposure of the sulfide residue to air and water initiated oxidation of sulfide minerals, forming an alteration zone 0.5 m thick. Arsenic accumulated in secondary phases, including X-ray amorphous iron sulfoarsenates (AISA), scorodite (FeAsO$_4$·2H$_2$O), and jarosite (H$_3$O$^+$,K)Fe$_3$((S,As)O$_4$)$_2$(OH)$_6$). Low solubility phases, including scorodite and jarosite, precipitated during the early stages of alteration. Scorodite occurred as microcrystalline aggregates, discrete grains, and inclusions in later AISA phases. Anhedral jarosite inclusions in AISA contained 0.94 wt% As in the upper alteration zone, and 2.2 wt% As in the lower zone of alteration. The prevalent secondary phase was reddish-yellow brown AISA, containing 16 to 37 wt% As. The As/S ratio of AISA decreased with progressive mineralization. The arsenic content in water infiltrating through the oxidized layers is controlled by the solubility of residual arsenopyrite and secondary As-phases.

The earliest stages of weathering were observed in the refractory wastes below the alteration zone, where the oxidative dissolution of arsenopyrite led to the release of arsenate, arsenite, sulfate and ferrous ions to pore water solution. Arsenic concentration in aqueous phases is controlled by the solubility of residual arsenopyrite and secondary As-phases in the alteration zone. Pore water in the unoxidized zone contains up to 100 mg/L total arsenic (up to 25 mg/L As (III)).

Additional keywords: arsenic, scorodite, jarosite.

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MIXING OF WASTE ROCK TO LOWER THE RELEASE OF Mg\textsuperscript{+2} AND SO\textsubscript{4}\textsuperscript{-2} AT ARGYLE DIAMOND MINE\textsuperscript{1}

Sunil Samaraweera\textsuperscript{2}, Rich Borden\textsuperscript{3}, Alvin D’Almaida\textsuperscript{2} and Ernst Griebel\textsuperscript{2}

Abstract. The seepage from the Argyle mine waste dumps is mildly acidic and contains high concentrations of magnesium (1400 mg/L) and sulfate (6500 mg/L). Out of the fourteen waste rock types mined, only Pv1 (with relatively low total sulfur content of 0.1 % to 1.0 %) causes a significant release of acidity and solutes. Only Pv5 possesses abundant acid neutralizing capacity and releases significant amount of Ca\textsuperscript{+2} during neutralization reactions. Experiments conducted in the laboratory have shown that when Pv1 is blended with Pv5 (ratio 2:1) a neutral pH solution, with about 1/10 the Mg\textsuperscript{+2} and 1/3 the SO\textsubscript{4}\textsuperscript{-2} is released compared to unblended Pv1 or blends made with other waste rock types. Argyle mine has recently implemented controlled co-disposal of these two rock types. The environmental and ecological benefits resulting from these changes into the waste rock management procedures will be assessed in the coming years.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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IRON AND MANGANESE REMOVAL IN A VERTICAL FLOW REACTOR FOR PASSIVE TREATMENT OF MINE WATER

Devin J Sapsford², Andrew Barnes², Matthew Dey², Keith P Williams², Adam Jarvis³, Paul Younger³, Liyuan Liang⁴

Abstract: Settling lagoons are a common feature of passive mine water treatment schemes but tend to require large surface areas, this makes them unfeasible in the numerous locations where space is limited. A novel pilot-scale vertical flow reactor has been built at the Taff Merthyr former colliery site. The vertical flow system is designed to replace conventional settling lagoons and decrease the surface-area requirements. To achieve this, the system is designed to take advantage of the surface-catalysed oxidation of Fe(II) on ochre surfaces and the (self)filtration of an ochre bed. This paper presents results from the first four months of operation and details iron and manganese removal. The system receives net-alkaline water from the abandoned colliery, the water quality is typically pH 6.9, with Fe_TOT of 9 mg/l. The results show that the vertical flow reactor achieves higher iron removal rates (typically between 10 and 20 g/m²/d) compared to the settling lagoon (typically < 5 g/m²/d). The vertical flow reactor achieves these removal rates with a smaller residence time, often half that of the settling lagoon. Manganese is present in the influent in low concentrations (~0.8 mg/l). Operating data show that about 50 % of Mn can be removed in the vertical flow reactor in 24 hrs compared to just 5 % in 24 hours in the settling lagoon. Longevity of the reactor will depend on maintaining an acceptable permeability in the bed. Although the permeability fell rapidly at first, the indications are that it is stabilising near to 10⁻⁴ m/s.

Additional Key Words: Surface catalysed iron oxidation

¹Poster 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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NATURAL ACID ROCK DRAINAGE ASSOCIATED WITH HYDROTHERMALLY ALTERED TERRANE IN COLORADO1

Matthew A. Sares2, Jeffrey P. Kurtz3, Dana J. Bove4, and John Neubert5

Extended Abstract

Introduction Acid mine drainage impacts on water quality from historic mining districts are well documented in Colorado’s mountainous areas. It is less well known that natural acid rock drainage (ARD) adversely affects water quality in eleven different headwater areas of the state. The geology of these areas is characterized by hydrothermal alteration, commonly related to volcanic activity, post-volcanic mineralization, or igneous stock emplacement. Areas of Colorado known to exhibit natural acid rock drainage include the Silverton Caldera, Lake City Caldera, Platoro-Summitville Caldera west of Alamosa; Kite Lake and East Trout Creek in the central San Juan Mountains; the La Plata Mountains; the Rico Mountains; Red Mountain and East Red Mountain in the Grizzly Peak Caldera southwest of Leadville; the Ruby Range; the Montezuma Stock west of Keystone; Red Amphitheatre northwest of Alma; and the Rabbit Ears Range (Fig. 1).

Methods Water from streams and springs was sampled to characterize water quality in hydrothermally altered geologic terrain. A total of 86 water samples were obtained from the altered areas (Fig. 1) in locations that appear to have no mining-related influence. In mining districts, water samples were obtained upstream or topographically above the influence of mining activity to confirm the presence of non-anthropogenic, natural acid rock drainage.

Several of these areas were then mapped, based on field observations and aerial photography, to determine the characteristics and the extent of alteration and various hydrothermal alteration types (Fig. 2). Rock samples were analyzed to identify mineral assemblages. In the expansive altered terrain of the Silverton Caldera, remotely sensed hyperspectral spectroscopic data augmented detailed field mapping to identify hydrothermal alteration areas and types.

Additional Key Words: alteration, headwaters, map, metals, standards, water quality

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POLLUTION OF A RIVER BASIN IMPACTED BY ACID MINE DRAINAGE IN THE IBERIAN PYRITE BELT (SW SPAIN)  

A.M. Sarmiento, J.M. Nieto, M. Olías & C.R. Cánovas

Abstract. The Iberian Pyrite Belt (IPB) is one of the most famous sulfide mining regions in the world. Mining activity in the IPB dates back to prehistoric times, and though today there is no active mining, the pollution continues to generate. The result is acidic drainage containing elevated concentration of sulfate and heavy metals. This is responsible for the pollution and degradation of the Odiel River basin in south-western Spain. In this work we have conducted a study along the entire Odiel basin. During the years 2002 and 2003 we have collected water samples at 69 points in order to characterize and quantify the pollutants that the Odiel River receives as a consequence of the AMD inputs within its watershed. The contaminant load transported by the Odiel River into the Huelva Estuary has also been calculated. Due to the great quantity of samples and analyses, the use of statistical multivariate techniques (Principal Component Analysis) was used to interpret the results. PCA of the samples showed strong interrelationships between the generation of acid by sulfide mineral weathering and metal loads. In downstream reaches, the rock forming elements (K, Ca, Na, Mg, etc.) dominate as the acidic waters dissolve the rocks in the stream bed. The contaminant load transported by the Odiel River to the Huelva Stuary is dominated by $\text{SO}_4^{2-}$, Al and Fe, with lesser quantities of Zn, Cu, Cd, etc.

Additional Key words: Odiel River, acid drainage, metal pollution.

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POST-BETZE PIT LAKE WATER QUALITY PREDICTION, NEVADA

William M. Schafer, Mark Logsdon, Guosheng Zhan and Ron Espell

Abstract - The Barrick Goldstrike Mine is located in the Carlin Trend, about 20 miles northwest of Carlin, Nevada. The majority of the ore mined at Goldstrike is from the Post-Betze open pit, the largest open pit operation in Nevada. Nevada law requires that the water quality of temporary or permanent reservoirs that may develop in open pits be periodically tested. Pit water quality prediction is conducted to monitor water quality and the possible impact that it may have on human, terrestrial, or avian life.

Water quality in the open pit at Goldstrike has been analyzed in three previous studies (BGMI 1991, Radian-Baker 1997, TRC 2000). The most recent analysis of the pit lake water quality model is discussed in this presentation. The effects of placing 516 million t of backfill waste rock into the open pit were also examined. This evaluation of pit lake water quality (Schafer and Logsdon 2003) differs from previous studies in that it utilized laboratory studies where natural groundwater from the site was mixed with water that had contacted weathered mine rock as a means of simulating the pit lake geochemical reaction path. Calibration of PHREEQC using batch test results enabled refinement of solubility data obtained from the thermodynamic mineral equilibrium database employed by PHREEQC. The prediction of pit lake hydrology and water quality involved six key elements including 1) summarizing the mine plan, and geochemistry of exposed rocks and backfill, 2) evaluating mine filling using a regional groundwater flow model, 3) conducting eight large-diameter column studies to generate representative rock contact waters, 4) performing batch mixing tests to simulate final pit water quality at various stages of filling, 5) calibrating a geochemical model based on the batch tests, and 6) using the calibrated model to predict water quality at various stages of pit lake recharge.

The uncalibrated PHREEQC model accurately predicted the common ion concentrations and pH of the batch tests, and correctly simulated the precipitation of large amounts of calcite when a mixture of various mine waters, groundwater and meteoric water was evaporated (although aragonite was actually the dominant solid that formed). Agreement between the model and batch tests was poorer for some metals, however. The PHREEQC model over-predicted zinc, nickel and antimony concentrations in the pit lake while under-predicting concentrations of barium, copper and arsenic. Calibration of PHREEQC enabled accurate prediction of trace element concentrations in batch tests, therefore improving its reliability for pit water quality prediction.

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PROBABILITY MODELING OF LONG-TERM MASS LOADS FROM A COVERED DRY-STACK TAILINGS FACILITY

William M. Schafer

Abstract: The Greens Creek Mine is an underground Zn/silver/lead/gold mine, lying partially within the Admiralty National Monument on northern Admiralty Island, Alaska. The mine is located approximately 18 miles southwest of the city of Juneau. The Greens Creek Mine began production in 1989. Mining was temporarily suspended from 1993 to July, 1996, but has continued to the present. The United States Forest Service recently completed an environmental review (EIS) of a planned expansion of the tailings facility submitted by Kennecott Greens Creek Mining Company. The quantity and quality of seepage from the tailings facility, and development of appropriate long-term water management strategies were key issues in the EIS. Three key alternatives considered in the EIS included:

- The proposed action would permit an increase in the size of the tailings disposal facility. Kennecott Greens Creek Mining Company (KGCMC) would continue its present method of generating whole tailings. The tailings would be placed without chemical or biological additives. After cessation of milling an engineered cover would be placed over the tailings to reduce the flux of water and oxygen into the tailings.
- Addition of carbonates to tailings to insure long-term neutral pH
- Addition of organic carbon to the pile to promote \textit{in situ} sulfate reduction

A stochastic predictive model was developed to estimate long-term chemical mass loads that may be generated from the dry-stack tailings. The model utilized empirical water quality data and cover performance monitoring and modeling to simulate the long-term geochemistry and hydrology of the tailings.

\footnote{Paper presented at the 7\textsuperscript{th} 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}

\footnote{Principal of Schafer Limited LLC, 3018 Colter Ave., Bozeman, MT 59715.}
APPLICATION OF GEO-ENVIRONMENTAL MODELS TO ACCELERATED EIA AND PERMITTING PROCESSES FOR AN ANDEAN PORPHYRY Cu-Au DEPOSIT

Ron L. Schmiermund, M. Cecilia Lazo, and Cynthia C. Parnow

Abstract. Current conditions in the global mining community have dramatically accelerated the quest for bringing projects on line with commensurate pressures being placed on every aspect of the permitting and planning processes. At the same time, the new realities of global communication, coupled with heightened environmental and social awareness, have placed local populations and special interest groups in much stronger positions to participate in those processes. In addition, governments and lending institutions are steadily becoming more sophisticated with respect to environmental and social liabilities while simultaneously wanting to encourage economic development. These competitive and frequently antagonistic interests create a need for efficiency, transparency and clarity in the permitting process and proactive approaches by mining companies.

This paper focuses on a Peruvian porphyry Cu-Au deposit with early social issues that prevented access to the property and existing samples needed for waste rock characterization. The EIA application process threatened to stall for lack of related environmental data. The principals of geo-environmental models were used to assimilate published data from analogous deposits in British Columbia and to create a defensible surrogate database to supplement the yet-inadequate site-specific data. Presentation of such estimates provided a mechanism to proceed with the permitting processes until local social and political issues could be resolved and appropriate environmental data collected.

Water quality data from several mines, as presented in the Red Chris, British Columbia project application for Environmental Assessment Certificate, is included, along with interpretations derived from equilibrium-based modeling. The information is used to substantiate and justify the choice of surrogate water quality parameters for acidic drainage from the Peruvian property in question. The surrogate composition was taken to temporarily represent dump seepage and sulfidic wall rock runoff and to estimate facility effluent and pit lake quality.

Geo-environmental modeling principals are shown to be useful for advance planning and proactive environmental planning, including situations where the permitting process has outpaced the availability of critical environmental data. Resulting data can be shown to be pragmatic and robust, less subject to interpretation than some other assumptions, as well as independent of the specific operator making the application.

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2 Knight Piésold and Co., Denver, CO 80265-2011
A MODIFICATION OF COLUMN-TYPE HUMIDITY CELLS TO ACCOMMODATE VERY FINE-GRAINED MINERAL PROCESSING WASTES\textsuperscript{1}

Ron L. Schmiermund\textsuperscript{2}

\textbf{Abstract.} Despite numerous shortcomings, kinetic testing incorporating a variety of humidity cell configurations remains an important component of mining waste characterization. The ASTM D 5744-98 and similar devices offer advantages for controlling experimental variables and increasing reproducibility. However, the design is limited in its ability to accommodate very fine-grained process wastes such as autoclave residues due to low permeabilities that restrict fluid movement and may impose diffusion-rate limitations on the oxidation processes. A method has been devised to impregnate fine-grained wastes in a highly permeable fiber substrate that appears to allow excellent access of both air and elution water to individual waste particles.

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} 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

\textsuperscript{2}Knight Piésold and Co., Denver, CO 80265-2011.
APPLICATION OF GEO-ENVIRONMENTAL AND BIOTIC LIGAND MODELS IN THE LIFE CYCLE OF MINE DEVELOPMENT – A FLOWCHART FOR INTEGRATION

Ron L. Schmiermund and James Ranville

Abstract. The traditional sequence and pace of events that occur following discovery and through mine permitting is increasingly unacceptable in light of global communications and heightened environmental and social sensitivity. Local and international NGOs can readily capitalize on corporate failures to be sufficiently environmentally and socially proactive. Eleventh-hour impact assessments are likely to be deemed inadequate and may cause significant financial losses. A flowchart has been developed to illustrate how geo-environmental and biotic ligand models (BLMs) might be used to promote timely, fiscally-responsible assessments of future environmental impacts. The approach parallels accepted methods of mineral resource assessment and mining property valuation.

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2 Knight Piésold and Co., Denver, CO 80265-2011. 3 Associate Professor, Colorado School of Mines, Golden, CO 80401
CCSA SYSTEM FOR TREATMENT OF ACID MINE DRAINAGE

Carlos Schneider

Abstract: This is a useful model for acid drainage generated by coal mining, including a system where the coal washing plant itself is used with advantage in the chemical and physical treatment of all the acid drainage generated at the mine site. This system applies a principle of conservation of the energy that is used in the coal dressing plant, involving all unit operations (water sumps and pumps, wet screening, jigging, cycloning, spiral classifiers and dewatering screening). This generates optimum interaction between the particles that are present in the ore and the acid drainage water that is used for processing in the plant. In this work, the influence of this increased interaction between the water and the ore particles is demonstrated. The working mechanisms are increased flocculation and aeration that result from processing. These aid in the correction of both pH and acidity, and also favor the oxidation of dissolved metals which, in turn, adhere to the flocs formed during processing and that can be discharged through thickeners or tailings pond. The tailings slurry contains particles smaller than 1 mm, which settle readily, producing clarified water. This clarified water can be easily separated from the underlying slimes, and can be considered as treated water, within the legal limits that are imposed by the local legislation. The slimes can be used as impermeabilizer in the coarse tailing stockpiles. Finally, the system consumes industrial alkaline residues that are produced in other industries, and which would otherwise be discarded as hazardous waste. Here, this material is used as an important resource in a neutralization process.

1 Poster 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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THE AZNALCÓLLAR PIT LAKE – WATER QUALITY AND OPTIONS OF CONTROL¹

Martin Schultze, Kurt Friese, Javier Sánchez and Enrique López²

Abstract: The Aznalcóllar mine is well known since the disaster in 1998. A dam of the tailings impoundment broke and about 4 million m³ of acidic water and 2 million m³ of sludge contaminated the river system Rio Agrio-Rio Guadiamar-Rio Guadalquivir with heavy metals. A lot of research has been done to quantify the consequences of the disaster for the river system and to prove the success of the remediation measures. But little is known about the state and the perspectives of the rising lake in the former mine pit.

Parts of the Aznalcóllar pit have been used to dump waste rock from the neighboring pit Los Frailes. Additionally, tailings material and contaminated soil from the river system were deposited in the former mine pit. Consequently, the pit lake sediments are very heterogeneous and highly enriched in heavy metals reaching ore-grade concentrations for some elements. Actually, the pit lake water level is regulated by pumping to stay at least 6 m below the natural groundwater level. The water is acidic (pH 3.6) and has high concentrations of metals (e.g. 800 mg/L Zn, 200 mg/L Mn, 100 mg/L Al, 2000 µg/L Cd). The major concern is that the contaminated lake water may enter the river system and the top aquifer when the lake reaches its natural water level.

Based on recent knowledge, options of future remediation of the lake water quality are discussed.

Additional Key Words: acidification, heavy metals, remediation

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PROCESSES CONTROLLING GEOCHEMICAL VARIATIONS IN THE SOUTH PIT LAKE, ELIZABETH MINE SUPERFUND SITE, VERMONT, USA¹

Robert R. Seal II², Laurie S. Balistrieri, Nadine M. Piatak, Christopher P. Garrity, Jane M. Hammarstrom, and Edward M. Hathaway

Abstract. The Elizabeth mine Superfund site offers unique opportunities to investigate the interplay between geochemical and physical processes in the geochemical evolution of an acidic pit lake. The mine exploited a steeply dipping massive sulfide ore body. Ores contained pyrrhotite and chalcopyrite and were hosted by siliciclastic sedimentary rocks and amphibolites. An open pit that accessed part of the ore body is filled by a long (380 m), narrow (< 25 m), and shallow (< 7 m) lake, which is divided into two parts by a rock slide. The southern end serves as a decant point, and discharges for most of the year. Quarterly sampling and continuous temperature monitoring of the water column in the lake document geochemical variations that depend on seasonal variations in the amount of precipitation and the presence or absence of ice. From spring to fall, parameters show limited variation with depth except for temperature, which decreases with depth. The lake experienced overturn in the fall. During winter under ice cover, the lake developed a chemocline shown by a sharp decrease in pH, a doubling of total dissolved solids (TDS), and a ten-fold increase in dissolved Fe with depth (0.4 - 55.2 mg/L). Oxida throughout most of the year causes removal of Fe, but low pH prevents significant sorption of Cu and other metals. Ca (25 - 72 mg/L), Mg (9.6 - 15.0 mg/L), K (6.0 – 8.3 mg/L), Si (6.7 – 9.6 mg/L), and SO₄²⁻ (210 - 280 mg/L) are the major dissolved constituents during non-stratified ice-free periods; Fe (0.2 - 0.5 mg/L), Al (1.0 – 3.1 mg/L), Cu (0.6 – 1.2 mg/L), and Zn (0.3 - 0.5 mg/L) are important minor dissolved constituents. Throughout the year, the water quality is dependent upon a variety of factors including the geometry of the pit, the short residence time of water within the pit, wind mixing and fall overturn, the oxidation of sulfides on the pit walls and in the unsaturated waste on the floor of the pit south of the haulage way, oxidation of iron within the water column, and mixing of surface waters with high TDS waters entering the bottom of the lake.

Additional Key Words: acid, copper, iron, massive sulfide, sulfate, seasonal

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MINING MITIGATION IN NORWAY AND FUTURE IMPROVEMENT POSSIBILITIES

Tom V. Segalstad\textsuperscript{2}, Ingar F. Walder\textsuperscript{3}, and Steinar Nilssen\textsuperscript{4}

\textbf{Abstract:} Norway has a long history of mining dating back to the Akersberg silver mine in Oslo about 1000 years ago. Larger-scale mining for copper and sulfur became common in the early 1600s. There is no active mining of massive sulfide deposits in Norway today; but the operations have left behind tailings, waste rocks and adits that in many cases discharge low-pH, metal-laden waste streams. Three of the Norwegian sulfide mines (Røros, Râna, and Sulitjelma) where mitigation has taken place, but metal release is still evident are discussed in this paper.

The Røros Mining District consists of many massive sulfide deposits mined primarily for Cu with minor lead and zinc. Some of the tailings dams have been reclaimed, while others have been left open exposed to weathering. Evidence of oxidation appears in the upper ½ meter in one of the uncovered tailings dams, closed 30 years ago, where pH is 2.5 at the surface increasing to a pH 6 at 70 cm depth. These tailings contain silicate minerals that most likely have a neutralizing potential.

The Râna mining area consist of a few smaller massive deposits and a recently closed (2002) nickel deposit associated with a mafic intrusive. Tailings from the nickel mine were emplaced along the shore line. Closure of the tailings included a soil cover 10-20 cm thick. Preliminary investigations indicate that this cover is not efficiently reducing the oxidation of sulfide minerals. Magnesium silicate minerals are most likely, however, neutralizing the acid generated from pyrrothite, the main sulfide in the ore.

The Sulitjelma Mining District also consists of many massive sulfide deposits mined until 1991. Reclamation of the mining district includes a one meter cover on the tailings dam and the discharge of ARD into old underground mine workings. This has resulted in a mass loading reduction of 80-90%.

Characterization of these sites has primarily focused on surface water quality, and in some instances, groundwater quality. The water quality data combined with mineralogical, geochemical, and hydrogeological data of the ore deposit and waste material can be used to improve mitigation, resulting in better control of metal release.

\textbf{Additional Key Words:} Røros, Râna, massive sulfide deposits, Sulitjelma, ARD, nickel, silicate mineral neutralization

\textsuperscript{1}Poster paper presented at the 7\textsuperscript{th} 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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CHARACTERIZATION OF THE WASTE ROCK AND PIT WALLS AT THE JUNDEE GOLD MINE SITE IN WESTERN AUSTRALIA AND IMPLICATIONS FOR LONG-TERM ISSUES\textsuperscript{1}.

Shannon Shaw\textsuperscript{2}, Jason Martin, Greg Meiers, Mike O’Kane, Christoph Wels

Abstract. The Jundee mine site is an open pit and underground gold mine located 50 km northeast of the township of Wiluna in central Western Australia’s desert. Jundee lies within the Archaean Yandal greenstone belt of the Western Australian goldfield. The area is deeply weathered and overlain by a thin veneer of alluvium and ferricrete. With the exception of satellite pits, open pit mining at Jundee ceased in 2002 and a number of open-cuts are being partially backfilled by waste rock, or tailings or left to flood with water. The primary sulfides in the waste rock and wall rock are pyrite and arsenopyrite. Carbonates are extensive on the site, consisting predominantly of calcite and ankerite. Given the rock types, mineralization and hydrothermal alteration of the waste rock, acid rock drainage is not anticipated; however, there is the potential for neutral drainage metal leaching and related water quality issues. Secondary mineral precipitates in localized areas include: hexahydrite, halite, gypsum, basanite, siderite and hematite. This paper describes the characterization program implemented, the results obtained and the implications for long-term issues at the site.

Additional Key Words: neutral drainage, metal leaching, salinity, hexahydrite, halite, siderite, basanite, gypsum, hematite.

\textsuperscript{1} Paper presented at the 7\textsuperscript{th} 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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THE CONTRASTING GEOCHEMISTRY OF SURFACE WATER IN THE TAILINGS OF CENTRAL MANITOBA GOLD MINE, CANADA

B. L. Sherriff and N. V. Sidenko

Extended Abstract  Heterogeneous distribution of minerals within a tailings deposit can lead to long-term establishment of different ecosystems. The 70 year old tailings deposit at the Central Manitoba Gold Mine contains two shallow ponds. The Blue Pond, which is about 1 m deep and 100 m in diameter, has a pH of 4.4 and is barren whereas the shallower Green Pond, 150 m away, is neutral (pH 7-8) with vegetation. The objective of study was to discover the reason for this difference in aqueous geochemistry and revegetation.

Figure 1. Central Manitoba Tailings, (500 m N-S and 1.5 km E-W). Discharge is presumed to be just south of the Blue Pond.

Additional keywords: acid mine drainage

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Abstract. The goal of many landowners who own reclaimed mined land is to restore the diverse mixed mesophytic forest for environmental, economic, and cultural reasons. However, native hardwoods tend to grow poorly on mined sites due to their physical, chemical and biological mine spoil properties. A 4 x 2 x 3 factorial greenhouse experiment was conducted with one-year-old seedlings. We examined the suitability of four growth media: forest topsoil (FT), weathered sandstone (WS), unweathered sandstone (US), and unweathered shale (UH), as well as the effects of inoculation with topsoil (none verses inoculated), on the growth of three native hardwood species: *Fraxinus americana*, *Q. rubra*, and *L. tulipifera*. Tree growth, foliar nutrients, and soil properties were measured and characterized. The WS was the mine spoil material most conducive to growth for *F. americana* and *Q. rubra*. *L. tulipifera* did not respond to any treatments. Foliar nutrient analysis indicated that adequate nutrition of *Q. rubra* was independent of spoil type (p = 0.49), *F. americana* was somewhat dependent on spoil type for nutrient uptake (p =<0.0001), and *L. tulipifera* was highly dependent, (p < 0.0001). Topsoil inoculation significantly increased growth on the UH spoil type, but not the US or WS spoil types. Topsoil inoculation significantly increased the number of herbaceous plants growing in the pots and improved foliar nutrient indices in *F. americana* and *L. tulipifera*. Many properties, such as pH, microbial activity, and water availability of the WS more closely approximated the control soil than the sandstone or shale. The results of this study show that trees are sensitive to spoil type and that certain spoil types should be selected during the reclamation process. Topsoil inoculation should also be considered as it may increase tree growth on some spoil materials, improve tree nutrition and help return the diverse native plant population that was present prior to mining.

Additional Key Words: mine reclamation, reforestation, topsoil substitutes.
ARD MANAGEMENT AT GEITA GOLD MINE

Ulrich Sibilski and Rebecca Stephen

Abstract: The Geita Gold Mine (GGM) is located approximately 4km west of Geita in the Mwanza Region of northern Tanzania. The mine is situated at the headwaters of the Mtakuja River that drains into Lake Victoria approximately 20km north west of plant site. GGM is owned and managed by AngloGold Ashanti Limited which is one of the major gold producer companies in the world. GGM alone produces up to 610,000 oz of gold per year moving towards 880,000 oz in 2007.

GGM has sound environmental practices and Acid Rock Drainage (ARD) is one of the main issues of concern. This paper describes the management of ARD at GGM which is mostly done through proper identification and handling of potentially acid forming waste material from all operating five pits. The procedure for ARD management involves: producing a waste model for the life of mine for each pit; validating of waste models using in-pit geological mapping; selective handling and placement of waste in designated areas of the waste rock dump and the tailings dam embankments; validating placement of waste within the waste rock dump and tailings dam embankment; monitoring the placement using piezometers within the waste rock dump, tailings embankment and downstream of these facilities; regular technical reviews and implementing the mentioned procedures for the life of mine. Our rehabilitation programme further enhances the combat of ARD and has been recognised in the Tanzanian mining industry as being the benchmark.

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MINERALOGICAL AND GEOCHEMICAL CHARACTERIZATION OF Ni-Cu SULFIDE TAILINGS, THOMPSON, MANITOBA, CANADA

Sidenko² N.V., Sherriff, B.L.³, VanGulck J.⁴

Abstract. To assess the mobility of metals and consider the geochemical consequences of remediation for exposed Ni-Cu tailings at INCO Ltd., Thompson, Manitoba, Canada, the tailings were described visually, characterized mineralogically, and subjected to sequential extraction and hydraulic conductivity tests. Exposure of the tailings has resulted in the release of metals from sulfides, the acidification of surface and shallow ground waters within the tailings body, and the formation of cemented hardpan layers. Sequential extraction from the solid tailings showed most of the Cu and Zn to be adsorbed by secondary Fe-minerals, while ~15% of the total Ni concentration occurs as water-soluble sulfates in the vadose zone. A rise in water level would result in the dissolution of soluble minerals and the remobilization of metals from the exposed tailings.

The formation and thickness of the cemented hardpan layers on the surface depend on the elevation of the water table and the degree of capillary action as this controls the moisture content of the pore space and hence sulfide oxidation. According to geotechnical measurements, the effect of cementation on reducing water flow through the hardpans to the interior of the tailings is insignificant, but the hardpan could act as a diffusive barrier for oxygen. In the hardpans, from 30 to 50% of sulfides are still not oxidized, and are, therefore, able to generate acid. The high acidity of the water at the surface of the exposed tailings prevents metals from being effectively co-precipitated by the secondary Fe-minerals, jarosite and schwertmannite. Thus, capping exposed tailings with acid neutralizing material is recommended.

Additional key words: tailings, sulfide oxidation, sequential extraction, jarosite, schwertmannite, hardpan, hydraulic conductivity

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THE SOURCE, ATTENUATION AND POTENTIAL MOBILITY OF ARSENIC AT NEW BRITANNIA MINE, SNOW LAKE, MANITOBA

Stephanie J. Simpson, Barbara L. Sherriff, Nikolay Sidenko, Jamie Van Gulck, and Kathleen Londry

Abstract: The source, attenuation, and potential mobility of arsenic are being investigated in surface and groundwater at New Britannia Mine, Snow Lake, Manitoba, Canada. Concentrations of arsenic, averaging 20.0 mg/L (1995 – 2005) persist in the groundwater at monitoring well 17 (MW17) below the former Nor Acme emergency tailings disposal area. Arsenic is toxic and mobile under typical surface and groundwater conditions (pH 5-9). Snow Lake is approximately 500 m from the mine and provides drinking water as well as a recreation site for the population of the town of Snow Lake.

During the early 1950’s, 227 000 tonnes of cyanide-treated, refractory sulphide concentrate with a grade of 9.60 g/tonne of gold were stored in an Arsenopyrite Residue Stockpile (ARS) in hopes of eventually developing a safe and economic means of extracting the refractory gold. The ARS, which contains pore water concentrations of arsenic up to 98.3 mg/L near the base of the pile, was capped in 1995 to prevent further oxidation of the sulphide concentrate and surface runoff. MW 17 is 100 m downgrade from the ARS.

The stockpile has been determined to be the most probable source of elevated arsenic concentrations to the groundwater at MW17. Hydrogeological modeling indicates a flux of $3.15 \times 10^{-9}$ m/s through the base of the pile into the underlying aquifer. Arsenic concentrations in the pore water extracted from the Nor Acme tailings are consistently low, ranging from 0.09 – 3.8 mg/L As. Arsenic levels decrease gradually with depth into the reduced zone, with the greatest concentrations occurring at the interface between the oxidized and reduced tailings. The total amount of arsenic bound to solids also decreases gradually with depth through the tailings.

Scanning electron microscopy (SEM) and electron microprobe analysis (EMPA) show arsenic bound to secondary phases comprising of Fe and Ca indicating that As may be adsorbed, with Ca, on Fe oxides and/or hydroxides.

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USE OF LAND CAPABILITY CLASSIFICATION SYSTEM IN THE
SURFACE MINING CONTROL AND RECLAMATION
ACT OF 1977 (PUBLIC LAW 95-87) 1

H. R. Sinclair, Jr. and Robert R. Dobos2

Abstract. The Surface Mining Control and Reclamation Act of 1977 (Public
Law 95-87) authorized the Secretary of the Interior to implement a regulatory
program to reduce the environmental impacts of coal mining operations. The
Secretary of Interior administers this program through the Office of Surface
Mining Reclamation and Enforcement (OSM) with assistance from state and other
federal agencies as specified in the law. All functions and responsibilities
assigned to USDA by Public Law 95-87 were delegated by the Secretary of
Agriculture to the Chief of USDA-NRCS, except those that relate to the National
Forest Service System Lands and to the USDA-Agriculture Research Service.
This paper briefly presents how the Land Capability Classification System can be
used in the development of rules, regulations, and guidelines for evaluating the
quality of soil reclamation after surface mining for coal. The Land Capability
Classification System can provide for compliance with Public Law 95-87. The
land capability of the reclaimed soils can be compared to the capability of the pre-
mined soils for producing crops.

Additional Key Words: farmland, grandfathering, historically used for cropland,
Land Capability Class, Land Capability Subclass, Land
Capability Unit, Soil Map Unit, soil component.

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Abstract: The duration of acid mine drainage (AMD) flowing out of underground mines is important in watershed restoration and abandoned mine land reclamation projects. Past studies report that AMD flows from underground mines for hundreds of years with little change, while others find that poor drainage quality only lasts 20 to 40 years. In northern West Virginia, 20 above-drainage underground mines with AMD discharges were located and sampled during 1968, 1980, 2000, and 2005. Water flow, pH, acidity, Fe, Al, and sulfate were measured at all sampling times. From earlier work, 33 out of 44 sites (77%) were found to improve in drainage quality between 1968 and 2000. The results of the 2005 water sampling period confirmed these earlier findings. Out of 20 sites in the present study, only nine sites gave sufficient flow for water samples to be taken again in 2005. Of these nine discharges sampled in 2005, two showed a 22% and 32% increase of acidity, while the other seven sites (78%) decreased in acidity between 64 to 93%. Further sampling will quantify acidity changes of the original 44 above-drainage underground mine sites and more water samples will be collected during all four seasons of the year, which will represent both wet and dry periods. In this way, quantification of the effects of flow on underground mine chemistry may be evaluated.
PREDICTING TOXIC EFFECTS OF COPPER ON AQUATIC BIOTA IN MINERALIZED AREAS BY USING THE BIOTIC LIGAND MODEL

Kathleen S. Smith, James F. Ranville, Marti K. Adams, LaDonna M. Choate, Stanley E. Church, David L. Fey, Richard B. Wanty, and James G. Crock

Abstract. The chemical speciation of metals influences their biological effects. The Biotic Ligand Model (BLM) is a computational approach to predict chemical speciation and acute toxicological effects of metals on aquatic biota. Recently, the U.S. Environmental Protection Agency incorporated the BLM into their regulatory water-quality criteria for copper. Results from three different laboratory copper toxicity tests were compared with BLM predictions for simulated test-waters. This was done to evaluate the ability of the BLM to accurately predict the effects of hardness and concentrations of dissolved organic carbon (DOC) and iron on aquatic toxicity. In addition, we evaluated whether the BLM and the three toxicity tests provide consistent results. Comparison of BLM predictions with two types of Ceriodaphnia dubia toxicity tests shows that there is fairly good agreement between predicted LC_{50} values computed by the BLM and LC_{50} values determined from the two toxicity tests. Specifically, the effect of increasing calcium concentration (and hardness) on copper toxicity appears to be minimal. Also, there is fairly good agreement between the BLM and the two toxicity tests for test solutions containing elevated DOC, for which the LC_{50} is 3-to-5 times greater (less toxic) than the LC_{50} for the lower-DOC test water. This illustrates the protective effects of DOC on copper toxicity and demonstrates the ability of the BLM to predict these protective effects. In contrast, for test solutions with added iron there is a decrease in LC_{50} values (increase in toxicity) in results from the two C. dubia toxicity tests, and the agreement between BLM LC_{50} predictions and results from these toxicity tests is poor. The inability of the BLM to account for competitive iron binding to DOC or DOC fractionation may be a significant shortcoming of the BLM for predicting site-specific water-quality criteria in streams affected by iron-rich acidic drainage in mined and mineralized areas.

Additional Key Words: bioavailability, toxicological testing, Ceriodaphnia dubia, ecological risk assessment, water chemistry, dissolved organic carbon, DOC, calcium, iron, metals, water-quality criteria, hardness

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MINERALOGICAL, GEOCHEMICAL AND ISOTOPIC STUDY OF THE ACTIVE TAILINGS IMPOUNDMENT CARÉN FROM THE PORPHYRY COPPER DEPOSIT EL TENIENTE, CHILE

Jochen Smuda, Bernhard Dold, Jorge Spangenberg

Abstract: At the active tailings impoundment Carén (surface 22 km²) from the porphyry copper mine El Teniente, Chile, initial steps of primary mineral alteration and geochemical changes after deposition were studied. The tailings contained up to 3 vol% sulfides (mainly pyrite). At five points in the tailings impoundment, water samples up to a depth of 4 m were taken from piezometer. Preliminary data showed that the water, which was entering the tailings impoundment as an alkaline (pH 9.21) tailings slurry, changed to neutral (pH 7.41) conditions at the discharge of clear water from a decantation lake into a natural river system. The discharged clear water contained Cu up to 80μg/L, Zn up to 180 μg/L, Mg up to 30 mg/L, Mo up to 0.35 mg/L and sulfate (up to 1400 mg/L) indicating the liberation of metals from the very early stage of sulfide oxidation. Initial water and mineralogical data indicated a 2-layer structure of the tailings: (1) the first layer (0 m -1 m depth) was dominated by the alkaline pH of the fresh tailings but with lower pH at the surface and higher pH at 1 m depth. Incipient pyrite alteration was observed at the surface already two weeks after deposition; pyrite grains also in the youngest layers showed small oxidation rims. This process seemed to lower the pH at the surface of the tailings impoundment. New tailings deposition renewed in a 4-weeks rhythm the alkaline conditions at the surface. (2) In the second layer (1 m to 4 m depth) the pH decreased down to near-neutral environment, possibly due to neutralisation of the bases by the tailings.

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GEOCHEMISTRY AND SECONDARY MINERALOGY AT THE SULFIDE-RICH EXCELSIOR WASTE ROCK DUMP FROM THE POLYMETALLIC Zn-Pb-(Ag-Bi-Cu) MINERALIZATION CERRO DE PASCO, PERU

Jochen Smuda\textsuperscript{2}, Bernhard Dold\textsuperscript{2}, Kurt Friese\textsuperscript{3}, Peter Morgenstern\textsuperscript{4}

Abstract. The Excelsior waste rock dump of the polymetallic Zn-Pb-(Ag-Bi-Cu) Cerro de Pasco deposit, Peru is characterized by high acid-production potential due to its waste rock composition with 60 wt% pyrite and <5 wt% carbonates. The waste dump is locally rich in minerals that contain up to 12.7 wt% Pb, 4.9 wt% Zn, 1.1 wt% Cu, 6020 mg/kg As, and 381 mg/kg Cd. Acid mine drainage (AMD) at the base of the waste rock dump is rich in Fe, Zn, Pb, Cd and As. The object of this study is to determine the source of metals in AMD and if metal contamination was related to seasonal fluctuations of precipitation. Main secondary minerals are gypsum, hydronian / plumbo- / K-jarosites, goethite, schwertmannite, and efflorescent salts (Fe-, Zn-, Mg-, Mn-sulfates). Leach tests of mine waste material simulated rain events and demonstrated the high solubility of efflorescent salts and acid/metal liberation. Leachates have pH between 2.8 and 4.9 and contain a maximum of 447.1 mg/L Zn, 16.7 mg/L Cu, and 14.8 mg/L Cd. AMD appears to be controlled by precipitation of secondary efflorescent salts in dry seasons and re-dissolution in rainy seasons.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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LABORATORY STUDIES OF SPHALERITE DECOMPOSITION: APPLICATIONS TO THE WEATHERING OF MINE WASTES AND POTENTIAL EFFECTS ON WATER QUALITY

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Abstract. Sphalerite [(Zn,Fe)S] from Mississippi Valley type (MVT), volcanogenic massive sulfide (VMS), and polymetallic vein (PMV) ore deposits show variable rates of dissolution and resulting aqueous metals concentrations under acid conditions. An important control on dissolution rates is solubilized iron that eventually produces Fe(III), a strong oxidant of sphalerite. VMS (high Fe and Cd) and PMV (high Fe and metals) sphalerite samples showed faster rates of sphalerite dissolution ($10^{-9}$ to $10^{-10}$ mol/L/s Zn\textsuperscript{+2}) and Fe solubilization ($10^{-9}$ to $10^{-10}$ mol/L/s total Fe), and higher aqueous trace metals compared to MVT sphalerite that has low Fe and trace metals; these characteristics are manifested by slower rates of sphalerite dissolution ($10^{-10}$ to $10^{-11}$ mol/L/s Zn\textsuperscript{+2}) and Fe solubilization ($10^{-12}$ mol/L/s total Fe), and low aqueous metals compared to VMS and PMV samples.

Aqueous concentrations of major (Fe, Zn) and trace (Cu, Cd, Pb, Mn) elements depended on the original composition and rate of dissolution of sphalerite. Fine-grained, high-Fe VMS sphalerite (6.7 wt.\%) leached at pH 2-3 (25° C) produced dissolved Fe and Zn approaching 50 and 180 mg/L, respectively, within 1 week; Cu and Pb were 3 and 250 μg/L, respectively. The same sphalerite leached at pH 4.0 or higher took two months to yield comparable concentrations. Coarse-grained VMS sphalerite leached for several months at a pH of 4.0 yielded only 100 μg/L Fe and 9.2 mg/L Zn. PMV sphalerite (4.2 wt.\%) had a Zn solubilization rate and trace metal concentrations similar to the VMS sample, but a faster Fe solubilization rate ($10^{-8}$ mol/L/s Fe\textsubscript{tot}).

Low-iron sphalerite (0.2-0.3 wt.\%) from MVT deposits produced Zn concentrations similar to the VMS sphalerite at pH 2.0 but lower concentrations at pH 4.0. At both pH values, aqueous Fe from the high-Fe VMS sample was 100 times that from the MVT sample. Trace metals showed a range of concentrations that generally depended on their original abundance in the solid and their solubilities in the acid solution. Because sphalerite from different ore deposits can be major sources of aqueous metals that may affect the composition of nearby surface and ground water, the potential metal contribution of non-pyritic minerals such as sphalerite should be a major consideration during all stages of economic development of an ore deposit.

Additional Key Words: acid drainage, mine waste, aqueous chemistry

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ADVANCES IN ACID ROCK DRAINAGE (ARD) CHARACTERISATION OF MINE WASTES

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Abstract. Research was carried out to improve acid rock drainage (ARD) prediction methodologies, focussing on resolving uncertainties in acid base accounting (ABA) methods. Advancements, their application, and interpretation are reported. Consideration of both net acid production potential (NAPP) and net acid generation (NAG) test results provide a more reliable routine screening technique than either test alone, increasing confidence in acid potential classification and identifying apparent conflicts requiring further investigation. Techniques such as sequential NAG, modified organic carbon NAG, modified ANC methods to account for siderite and acid buffering characteristic curve (ABCC) testing can be used to help resolve these conflicts in a relatively short time frame. Samples with abundant siderite require complex modified ANC methods, involving excess addition of H$_2$O$_2$ to ensure all dissolved ferrous ion is oxidised before completion of the back titration step. It is demonstrated that at siderite abundances of less than 15 wt %, standard ANC methods are sufficient, improving the efficiency of ANC assessment by reducing the number of modified ANC tests required.

Comparison of ABCC profiles with the developed set of standard carbonate curves provides an indication of the relative reactivity of the ANC measured in waste rock samples, something not evident in ANC test results alone. A relationship was established between kinetic NAG and leach column test results, which provides an indication of lag times without the need to carry out leach columns on all samples. This has the great advantage of allowing kinetic prediction on a broad sample set in a short time frame. The test refinements and developments described in this paper improve the reliability of ARD prediction from short duration tests, provide information on relative reactivity of acid forming and neutralising phases, and improve predictions of acid forming potential.

Additional Key Words: NAG, ANC, NP, NAPP, NNP, ABA, ABCC, kinetic NAG, siderite, leach column
ALKALINITY PRODUCING COVER MATERIALS FOR PROVIDING SUSTAINED IMPROVEMENT IN WATER QUALITY FROM WASTE ROCK PILES.

Jeff Taylor, Bill Guthrie, Nigel Murphy and John Waters

Abstract. Acidic and Metalliferous Drainage (AMD) from sulfidic waste rock piles is a major issue facing the mining industry worldwide. Existing dry cover systems are designed to minimize the acid load discharged from waste rock piles by lowering infiltration rates. The strategic blending of alkaline amendments, such as limestone, within waste rock piles is also used to minimize the acid load discharged. The benefit of this blending is limited in most cases due to armoring (passivation) of limestone by precipitates.

Armoring can be overcome by placing limestone on top of the waste rock piles, where it only interacts with rain water. Alkalinity released from the limestone-bearing covers can react with acid and metallic salts along preferential flow pathways within a waste rock pile to create inert, precipitate-coated channels that inhibit further reaction (i.e. acid release). Due to the low solubility and slow dissolution rates of limestone, acid generation is not completely prevented and may still occur within the waste rock pile. Nevertheless, an overall reduction in the physical interaction between water and acid producing materials can sometimes be achieved using limestone-bearing covers. This mechanism has proven successful at the Freeport mine in Indonesia, which is characterized by very high rainfall. However, the effectiveness of limestone-bearing covers is limited under most climatic conditions, as a result of the low solubility and slow dissolution rates of limestone in near-neutral rainwater.

New magnesium-based materials with superior solubility and dissolution rate characteristics to limestone have been developed for use in waste rock covers. These materials will permit the controlled release of alkalinity to infiltrating rainwater over a wide range of climatic conditions.

The required amount of the magnesium-based alkalinity producing material in a waste rock cover will be insignificant relative to the amount of acid producing material in the waste rock. As a result, the magnesium-based cover materials represent an innovative and cost-effective solution to minimization, rather than treatment, of acid drainage from waste rock piles.

The new materials being developed are based on calcium-enriched caustic magnesia (MgO) with controlled calcination grades and grain sizes to maximize both solubility and dissolution kinetics. Alkalinity concentrations of up to 510 mg/L CaCO₃ equivalent in pure water can be achieved with the new materials (c.f. only 10-15 mg/L for limestone), with a typical saturation pH of 9.0-9.5 (c.f. only 8.0-8.5 for limestone).

Compared to limestone it is envisaged that relatively small amounts of these new magnesium-based materials can be deployed within existing and new cover systems to minimize short, medium and long term acid discharges, thereby providing a significant advance in the control of AMD (acid and metalliferous drainage) from waste rock piles.

Additional Key Words: store and release covers, alkalinity producing cover materials, caustic magnesia, acid and metalliferous drainage (AMD), acid and metalliferous drainage.

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Abstract. Sustainable development has become a driving force in how the mining industry approaches all existing and future activities. Progress has been made to advance environmental performance and stewardship and provide benefits to civil society. Technologies are now in place to plan for, open, operate and decommission a mine property in an environmentally acceptable manner, both in the short and long term. Moreover, mining companies, governments and consultants have acquired a great deal more capability to deal with environmental and societal issues such as water contamination from mine wastes, including acid generation.

The Mine Environment Neutral Drainage (MEND) program was the first international multistakeholder initiative to develop scientifically-based technologies to reduce the effect of acidic drainage. The original program (1989-1997) and its successor, MEND 2000 (1998-2000) contributed enormously to the understanding of acidic drainage and how to prevent it. MEND focused the acidic drainage effort and developed a toolbox of technologies that is available to all stakeholders. Despite this progress, acidic drainage remains one of the most significant environmental issues facing the mining industry. In 2001-2002 MEND laid the groundwork for a renewed research program by identifying Canadian national and/or regional priorities through a strategy session and subsequent survey. Since then, many of these priorities are being addressed through projects, workshops, reviews on emerging technologies and guidance documents.

MEND is a partner in the Global Alliance, an international alliance between regional groups involved in acidic drainage research. This group will continue its collaboration to enhance technology transfer towards improving the understanding of acidic drainage.

The successes of MEND and other partnership programs have come through the cooperative efforts of the partners, the sharing of experiences, the thorough evaluation of technologies and practices. Through these efforts a significant advancement in environmental management is achieved and thus has contributed to the long-term sustainability of the mining industry and the environment.

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AMD Treatment in New Zealand – Use of Small-scale Passive Systems

Dave A. Trumm, Malcolm Watts, and Peter Gunn

Abstract. The general goal of passive AMD treatment is to reduce levels of acidity and metals to acceptable levels. Most treatment systems use either an oxidizing or a reducing strategy. In oxidizing systems, alkalinity is added along with dissolved oxygen; in reducing systems, dissolved oxygen is removed (if present) and then alkalinity is added. To test the applicability of oxidizing and reducing strategies to treat AMD, small-scale passive treatment systems have been constructed and tested successfully at two sites on the west coast of the South Island, New Zealand. At the Sullivan Mine, a reducing system consisting of a vertical-flow wetland reduced the levels of acidity by 100%, iron by 97%, aluminum by 100%, and nickel by 66%. The Pike River Coal Company has shown foresight by using the same system to treat AMD at a small adit within the Pike River Coal Field. The system reduced acidity by 100%, iron by 99%, aluminum by 96%, nickel by 95%, manganese by 51%, and zinc by 99%. At a third AMD site, the Blackball Mine, a laboratory-based experiment was used to test the applicability of an oxidizing system for AMD treatment. In the experiment, AMD was passed through a limestone leaching column over a nine-day period. Acidity was reduced by 100%, iron by 83%, aluminum by 82%, manganese by 8%, and zinc by 64%. To determine if this treatment method reduces the toxicity of the AMD to aquatic invertebrates, a 96-hour ecotoxicity experiment was conducted. The results show a significant decrease in mortality in the treated AMD compared to untreated. These small-scale systems and laboratory-based experiments suggest that a full-scale treatment system using a reducing strategy may be successful at the Sullivan and Pike River Mines and that a system using an oxidizing strategy may be appropriate for the Blackball Mine.

Additional Key Words: AMD, acid rock drainage (ARD), Pike River, Sullivan Mine, vertical flow wetlands, successive alkalinity producing systems (SAPS), water treatment

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ACID DRAINAGE TECHNOLOGY INITIATIVE: TEN YEARS OF MINING INDUSTRY, GOVERNMENT AGENCIES AND ACADEMIA COLLABORATION IN THE METAL AND COAL MINING SECTORS IN THE USA

Dirk J.A. van Zyl, Stephen Parsons, Virginia McLemore, and Roger J. Hornberger

Abstract. The Acid Drainage Technology Initiative (ADTI) was initiated in 1995 by federal agencies, the National Mining Association and the Interstate Mining Compact Commission to identify, evaluate and develop cost-effective and practical acid drainage technologies. In 1999, ADTI was expanded through the addition of the metal mining sector, which is focused on drainage quality issues related to metal mines. ADTI addresses drainage quality issues from abandoned, active, and future coal and metal mines.

The guiding principle of ADTI is to build consensus among industry, federal and state regulatory agencies on acid drainage technology development and technology transfer issues. ADTI is focusing its efforts on mine drainage prediction, sampling/monitoring, modeling and avoidance/remediation. ADTI is not a regulatory or policy development program.

ADTI includes the Coal Mining Sector and the Metal Mining Sector under the overall guidance of the ADTI Operations Committee. The Operations Committee consists of representatives from industry, state and federal government and academia. The Coal Mining Sector recently formed a number of groups to address a wide range of topics. The following groups have been formed: Water Quality, Coal Combustion By-Products (CCBs), Underground Mining, Passive Treatment, Technology Transfer. White papers have been prepared on 18 topics that are currently being studied. The Metal Mining Sector includes a steering committee and work groups on prediction, sampling and monitoring, modeling, mitigation, and pit lakes. The Metal Mining Sector has a committee that works with the Questa mine of Molycorp in the review of the waste rock pile study.

Since 2003 ADTI is the US organizational partner of The International Network for Acid Prevention (INAP). The partnership is continuing and is strengthened through closer cooperation and communication. This paper will provide details of progress over the last four years.

Additional Key Words: proceedings, organization, federal agencies, state agencies

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SURFACE PASTE DISPOSAL OF HIGH-SULFIDE TAILINGS – FIELD CELL MONITORING AND PILOT PLANT TESTING

Rens Verburg, Phil Newman and Mark Fordham

Abstract. Since 2001, Somincor have been investigating the feasibility of changing the tailings deposition method to sub-aerial placement of paste at its Neves Corvo Mine in southern Portugal. The pyritic tailings have a very high acid generation potential and are currently being placed sub-aqueously in a conventional tailings facility. Work completed to date has included a laboratory bench-scale screening program, a three-year field cell monitoring program, and pilot plant testing to investigate deposition techniques, co-disposal with acid-generating waste rock and cover performance. This paper describes the results of the field cell study and provides an introduction to the ongoing pilot plant testing.

Although the field cells exhibited short-circuiting of seepage, the field cell monitoring program has demonstrated that a considerable lag time exists before acidic seepage is generated. This lag time has important consequences in terms of operational placement of paste and closure of a paste deposit. Based on geochemical modeling and observations from the bench-scale testing program, long-term seepage quality may reflect buffering by kaolinite.

A pilot plant paste program has been ongoing since February 2005. This large-scale test (a 1-hectare site containing 35,000 m³ of paste) provides an exceptional opportunity to investigate paste deposition techniques. In addition, co-mixing with waste rock will be evaluated, as well as the long-term environmental stability of the paste. After paste deposition has been completed, the pilot area will be capped using several trial covers and its geotechnical and environmental performance will be monitored.

Additional Key Words: geochemical modeling, oxidation,
MANAGING A CAPPED ACID ROCK DRAINAGE (ARD) REPOSITORY USING SEMI-AUTONOMOUS MONITORING AND MODELING

Roelof Versteeg, Ken Wangerud, Alex Richardson, Trevor Rowe and Gail Heath

Abstract. Effective ARD repository management requires ongoing assessment of remedial integrity and operational performance in such a manner that short and long term risks and cost are balanced and optimized. Such management requires actionable information on the behavior of the repository. This information will typically be derived from diverse data (physical, chemical and hydrological), forward and inverse hydrological, geochemical and geophysical models and cost/benefit models. With the increase in volumes of data and complexity of analysis, end users face increasing challenges in obtaining information in a timely and cost effective manner. A web accessible workflow environment for performance monitoring, designed at the Idaho National Laboratory (INL), was implemented for a capped ARD repository (the Ruby Gulch Repository) and is part of the Gilt Edge Superfund site in South Dakota. This repository is instrumented with a geophysical, hydrological and environmental sensor network. Data from this network are transmitted automatically every two hours to a server. At the server, the data are automatically parsed in a relational database and analyzed using automatically executing scripts. The resulting information is both transmitted through automated reports and accessible by users through a web application. The combination of near real time reporting and analysis and integration with analysis tools provides for actionable information on short and long term repository behavior. The structure of a web accessible workflow system for performance monitoring is well suited for both managing data, creating information and providing access to information for diverse users.

1 Poster 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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GEOCHEMISTRY AND MINERALOGY OF THE QUIULACOCHA TAILINGS IMPOUNDMENT FROM THE POLYMETALLIC Zn-Pb-(Ag-Bi-Cu) DEPOSIT CERRO DE PASCO, PERU.

Cheikh Wade², Bernhard Dold³*, and Lluis Fontboté²

Abstract: The Quiulacocha tailings cover 114 ha, comprising 79 Mt of tailings, which contain ~ 50 wt% pyrite. The tailings are located at 4340 m altitude in a tropical puna climate with about 1025 mm/a rainfall. The tailings are partially overlain by the Excelsior waste-rock dump, which contains about 26,400,000 m³ of waste rocks that cover 94 ha and contain ~60 wt% of pyrite. In the Quiulacocha impoundment there are two different types of tailings recognized: 1.) Zn-Pb-rich tailings and 2.) Cu-rich tailings. During the sampling campaign, the Zn-Pb-rich part of Quiulacocha was not producing important excesses of acid mine drainage (AMD) from the oxidation zone, where pH is increased to near neutral values at 1 m depth. The underlying tailings were able to neutralize the acidity produced in the oxidation zone through sulfide oxidation by the underlying carbonates (dolomite and siderite). The main source of AMD in this mine-waste system is from the Excelsior waste-rock dump. Its acid seepage infiltrates into Quiulacocha forming a Fe-Zn-Pb plume with a pH 5.5 – 6.1 and containing up to 7440 mg/L Fe, 627 mg/L Zn, and 1.22 mg/L Pb. The plume was detected between 10 m to 13 m depth in the stratigraphy of Quiulacocha tailings. Additionally, the AMD seepage from the base of the Excelsior waste-rock dump is channeled on the tailings surface to the pond of Quiulacocha (pH 2.3), which covers Cu-rich tailings. Infiltration of this Fe(III)-rich AMD increases oxidation of tailings in the southwestern part of the impoundment and subsequently liberates As by enargite oxidation. Additionally, the AMD collected in the Quiulacocha pond was pumped into the active Ocroyoc tailings impoundment, where sulfide oxidation was strongly enhanced by the input of dissolved Fe(III). Therefore, a hydrological separation of the different mine-waste systems might be a first step to prevent further extension of the AMD problem.

Additional Keywords: Flotation, tailings, waste-rock dump, cemented zone, hydrology, acid mine drainage

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HYDROGEOCHEMICAL CHARACTERIZATION OF EFFLUENT FROM MINE WASTE ROCK, CLUFF LAKE, SASKATCHEWAN

Karin Wagner, Leslie Smith and Roger Beckie

Abstract. The interaction between geochemical and hydrological processes in waste rock was evaluated in an instrumented waste rock pile as part of ongoing studies into the scale-up of water chemistry predictions. Sulfate and metal concentrations were determined in both pore water and outflow waters collected in sixteen basal lysimeters over a four-year period. The waste rock contained approximately 0.5% sulfur as pyrite/pyrrhotite and was acid generating. The correlation between outflow rate and concentrations was negative during times when macropore flow was active and positive over longer periods. Sulfate concentrations greater than 40,000 mg/L and elevated metal concentrations including cobalt, manganese, nickel, strontium, uranium and zinc were observed in the acidic (pH ~ 3.6) pore water and outflow water. Over the four–year experiment approximately 5% of the initial sulfur was released at the base of the pile. Predicted sulfide oxidation rates determined from laboratory experiments were up to four times higher than the rates inferred from the field experiment (0.1 mg SO$_4^{2-}$/kg rock/week to 19 mg SO$_4^{2-}$/kg rock/week). A lower-permeability cover placed on the surface of the waste rock pile three years after the experiment started induced a decrease of the dissolved load in the effluent from a pre-cover average of 4.8 mg SO$_4^{2-}$/kg rock/week to 1.2 mg SO$_4^{2-}$/kg rock/week.

Additional Key Words: acid rock drainage, geochemistry, mass loading.

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HYDROGEOLOGICAL AND GEOCHEMICAL CHARACTERIZATION OF A WASTE ROCK PILE FROM A PORPHYRY COPPER DEPOSIT IN THE SEMI-ARID SOUTH WEST USA


Abstract. Over the last 15-20 years, there has been a large emphasis on tailings geochemistry and hydrogeology. Waste rocks piles, on the other hand, have received much less attention. Especially in the porphyry copper mining industry, waste rock piles can represent a larger potential for groundwater and surface water contamination than tailings since the waste rocks are commonly unsaturated and coarse. This setting allows for greater oxygen availability throughout the pile, thus increasing the oxidation potential. In general, there are three flow systems within waste rocks: macro flow (high flow); matrix flow (low flow) and micro flow (within particles) that together with waste rock composition affect seepage water quality. These systems have been investigated at the Tyrone Mine.

Continuous seepage water quality monitoring was performed at one of the stockpiles for approximately one year. The selected stockpile consisted primarily of oxide material with low sulfide content, and had never been leached. Seepage was observed throughout the year and seepage monitoring consisted of flow rate, pH and electric conductivity measurements. Waste rock samples were analyzed for acid base accounting and mineralogy, and kinetic tests were performed. The flow rate together with rainfall, hydrogeological data from the stockpile, stockpile infiltration and evaporation rates, and groundwater recharge rates were used to calculate macro/matrix components in the system using the kinematic wave theory. The results of this modeling indicated that only approximately 10 % of the infiltrating rainwater flowed through the macro pores all the way to the bottom. The majority of the water flowed through the matrix.

Water quality monitoring showed a pH increase during low flow periods and a rapid drop during heavy rainstorms. Electric conductivity had a slow decrease during the dry periods and a drastic increase shortly after heavy rainstorms. The geochemical data indicated a buildup of easily leachable secondary acid generating minerals during the dry periods that were being leached during heavy rain storms. The matrix also possessed a neutralizing effect from silicate mineral dissolution that was working effectively only in the slow matrix flow zones.

Additional Key Words: macro flow, micro flow, waste rock oxidation, silicate mineral neutralization

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Abstract. A major difficulty facing many open pit mines where sulfides are present is the pit lake water quality after closure. A reliable prediction of future water quality within an open pit mine, excavated below the water table, requires a large amount of information and predictions for maybe hundreds of years into the future. These long-term predictions can only be useful with thorough understanding of geochemical and hydrological processes of pit walls and surface water and groundwater discharging into the pit during mining and at closure.

Tyrone Mine initiated a pit-lake water quality evaluation as part of a closure evaluation. This involved characterization of waste rocks near the mine pit; determination of groundwater discharge and recharge into and from the pit using numerous wells drilled in the vicinity and monitored over many years; analysis of existing pit lake water quality over many years including a period of seven months with no pumping; water quality data from monitoring wells; local climate measurements; simulated rainfall leaching tests; and waste rock discharge water analysis.

A modeling scenario was set up dividing the groundwater recharge/discharge into 5 zones based on groundwater flow and geochemistry. The hydrogeological model was calibrated based on the monitoring data where recharge or discharge volumes for each of the zones were calculated. Surface runoff water quality was based on three different mineralogical zones that had a distinctly different leaching potential: an oxide zone with neutral pH and low total dissolved solids; a Chalcanthite zone with weakly acidic and very high TDS (in particular sulfate and copper); and a sulfide zone with low pH and high sulfate.

Pit lake modeling was performed to simulate the water quality observed during a seven-month period when there was no pumping taking place in the Main Pit. The model was calibrated with surface runoff and mineral precipitations. This modeling indicated that pit wall runoff was the most important control on water quality, and that the runoff water quality could be well represented by using in-field rainfall simulated leach tests.

Additional Key Words: weathering tests, porphyry copper deposit, Tyrone Mine, pit walls

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INSIGHTS INTO HYDRODYNAMIC AND GEOCHEMICAL PROCESSES IN A VALLEY-FILL ARD WASTE-ROCK REPOSITORY FROM AN AUTONOMOUS MULTI-SENSOR MONITORING SYSTEM\(^1\)

Ken Wangerud, Roelof Versteeg, Gail Heath, Rich Markiewicz and Alex Richardson\(^2\)

Abstract. Acid mine site remediation is a significant problem, both in the U.S and globally. Due to the volume of acid producing rock the only practical solution is minimizing acid production by reducing or eliminating water flow through the rock. Typically, this is achieved through emplacement of a cap over the waste rock. The Ruby Gulch repository at the Gilt Edge Mine NPL Site is such a capped waste rock repository. Eliminating discharge from valley-fill capped waste-rock repositories is difficult and multiple factors can cause continuing oxidation and ARD discharge. Consequently, early in the cap-cover design EPA and the Bureau of Reclamation design-build team recognized the need for a long-term monitoring system which would provide actionable information on the repository performance and behavior. Specifically, the following objectives were defined for a monitoring system: 1) provide information on the integrity and performance of the newly constructed surface cover and diversion system; 2) continuously assess the waste's hydrological and geochemical behavior, such that rational decisions can be made for the operation of this cover and liner system; 3) provide easy and timely information access on system performance to a variety of stakeholders; and 4) generate information and insights which can be used to enhance future cover and monitoring discussions between EPA, the Bureau of Reclamation and DOE Idaho National Laboratory. A long-term monitoring system was designed and integrated into the multi-layered geomembrane-rock-soil cap-cover over the 65-acre, 450’-high, sulfide waste-rock dump to provide information to meet these objectives. The system consists of tensiometers, lysimeters and thermocouples in four wells, a 523-electrode resistivity system installed below the cap and in the wells, a weather station, and a precision outflow-meter at the toe-discharge of the repository. Continuous data from this system as well as auxiliary manually collected samples are parsed into a web accessible central server. Automated and on demand data processing allows for 2-D, 3-D and 4-D resistivity tomography and user controllable data mining. The philosophy underlying this system is that it should provide both for effective automated and autonomous data collection and for a cost effective way for multiple stakeholders to use this data.

\(^1\)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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CASE STUDY ON THE REMEDIATION OF THE DEFUNCT COAL MINE ARBOR COLLIERY, IN MPUMALANGA SOUTH AFRICA

Chris Waygood, Mike Palmer, Rod Schwab

Abstract. Arbor Colliery is an abandoned colliery in the Loskop Dam catchment. The mine comprises a series of opencast pits, as well as poorly defined underground workings. The water within the opencast pits shows high levels of acidity, elevated sulfate levels and elevated metals (Al, Fe and Mn). Some 100 families live adjacent to the mine, and this presents interesting social challenges in terms of remediation. The mine will be rehabilitated over a period of several years. The remediation strategy proposed is discussed, together with some of the ongoing tests and issues still to be resolved.
SHORT-TERM ACID ROCK DRAINAGE CHARACTERISTICS DETERMINED BY PASTE pH AND KINETIC NAG TESTING: CYPRESS PROSPECT, NEW ZEALAND

Paul A. Weber, Joseph B. Hughes, Liam B. Conner, Phil Lindsay, Roger St. C. Smart

Abstract. The paste pH test (1 part solid: 2 parts water) is one method used to determine the acidic nature of a rock/soil sample. In conjunction with kinetic NAG testing a classification scheme has been developed for the Cypress Prospect within the Stockton coal mining region, West Coast, New Zealand. Samples having a paste pH of < 4.0 are considered potentially acid forming (PAF) and contain significant acidic sulfate salts (up to 30.1 kg H$_2$SO$_4$/t equivalent) that will immediately produce acid upon exposure to water. Samples with a paste pH of 4.0 – 5.0 are considered PAF, but have a lower stored acidic salt content (up to 9.0 kg H$_2$SO$_4$/t equivalent). In the field the lithologies represented by both these rock types are likely to generate ARD immediately upon exposure to water. Circum-neutral paste pH values (> pH 5.0) for samples classified PAF indicated that they have a short-term acid neutralization capacity (ANC) that is greater than the readily available short-term acid generating capacity of the sample. This resulted in a time lag (2 – 356 minutes) prior to decrease to pH 4 in the kinetic NAG test. Samples having a paste pH > 6.0 typically produced a longer lag period than those with a paste pH of 5 – 6. As previous researchers have demonstrated this represents a lag period prior to the onset of laboratory acid rock drainage in larger column leach tests. These results have direct application to strategic mine planning at the proposed Cypress mine including separating waste rock into immediate acid generators (high management priority) from acid generators with a lag to acid formation (lower priority) and non-acid forming. Field validation of this classification system is still needed.

Additional Key Words: Acid Rock Drainage, Kaiata mudstone, New Zealand
ASSESSMENT OF GROUNDWATER IMPACTS AT THE HISTORIC MOUNT MORGAN MINE SITE, QUEENSLAND, AUSTRALIA

Christoph Wels, Laura Findlater and Chris McCombe

Abstract: The Mount Morgan Mine is a historic mine site located in Central Queensland, Australia. Between 1882 and 1981, a total of 7.6 million ounces of gold and 360,000 tonnes of copper were extracted using underground and later open mining methods. The mine closed in 1990 after the re-treatment of 28 Mt of tailings, which were placed into the open cut. Most of the mine waste is acid-generating and acidic runoff and seepage has heavily impacted portions of the adjacent Dee River.

A groundwater flow model was developed for the Mount Morgan mine site to evaluate current seepage conditions and assess closure options. The calibrated groundwater flow model indicates that the backfilled (and flooded) Open Cut/Sandstone Gully represents the largest single source of ARD seepage (8.0 L/s) on the site with tailings impoundments representing important secondary sources of seepage. An estimated 80% of all seepage is collected in a seepage interception system (SIS). The remaining 20% (or ~3 L/s) of ARD impacted seepage by-passes the SIS and enters the Dee River and underlying aquifer.

The model predicts that seepage from the open cut would increase exponentially with a further increase in the water level in the open cut. The model suggests that a grout curtain or sealing the upstream side of Sandstone Gully Dam using a “blanket” of low permeability tailings would reduce seepage out of the open cut by about 40%. The amount of seepage reduction in response to placing a dry cover system onto mine waste (tailings and mine rock) is predicted to vary significantly across the site. The modeling results suggest that a combination of rehabilitation measures (including the placement of dry cover system and measures to control seepage out of the flooded Open Cut/Sandstone Gully) will be required to effectively control seepage at Mount Morgan. The calibrated groundwater flow model is currently being used to assess the effects of different closure scenarios (e.g. cover placement versus full relocation) on seepage rates and loading to the Dee River.

Additional Key Words: acid rock drainage, mine closure, hydrogeology

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BIOLOGICAL TREATMENT OF ACID MINE DRAINAGE AT THE ISLAND COPPER MINE PIT LAKE: RESULTS FROM AN ENCLOSURE STUDY

M.E. Wen, G.W. Poling, C.A. Pelletier, J. Chapman, E.L.J. Bingham

Abstract. The Island Copper Mine near Port Hardy, British Columbia, closed in 1996. The open pit was flooded with seawater by temporarily connecting the pit with adjacent Rupert Inlet. The flooding channel was then closed and the lake was then capped with freshwater piped from the Marble River to create a stable meromictic lake. Waste rock dumps generate Acid Mine Drainage (AMD) with elevated cadmium, copper and zinc that drains to the pit lake. The lake receives some 3M m$^3$/year of AMD (Zn 3 mg/L) directly on the surface and an additional 1M m$^3$/year of AMD (Zn 8 mg/L) injected at depth. Biologically mediated metal removal in the surface layer has been optimized through the surface application of a 6N:1P (by weight) liquid fertilizer. Concentrations of dissolved metals in the surface layer have been low (Zn <0.2 mg/L) since year round fertilization of the lake began in 2001. The treated water drains slowly through a porous, and mostly submarine, shoreline fill to the marine receiving environment of Rupert Inlet.

A pilot test facility was recently constructed in the pit lake to assure the effectiveness of AMD treatment for Island Copper in the long term. The test facility included two 90 m diameter floating rings supporting an 11 m deep polyethylene barrier curtain, head tanks, pipe works, valves and a control system to manipulate the chemistry in the two enclosures. By manipulating the flow of feed water from two distinct AMD sources into the enclosures, we tested two very different approaches to treating water in the pit lake. We present results from this experiment and discuss their use in the design of a novel full-scale AMD treatment system for Island Copper.
Abstract. German Pit Lake Bärwalde has been flooded since 1997 with surface water. Its current volume is $100 \cdot 10^6$ m$^3$ with a maximum depth of 50 m. Waste rock consists of porous media, with a medium sulfide-S content of 0.3 wt%. The dimictic lake is acidic. Comparison of the monitoring data and earlier predicted model results give a good insight into the governing processes at the site. Modeling of the lake's internal processes with MODGLUE shows that the water quality of Lake Bärwalde is dominated by the import and export of acidity and alkalinity. Existing models were partly modified and coupled. Internal production of alkalinity due to primary production was included based on the water quality algorithms of the model CE-QUAL-W2. This model was modified to handle changing pH and alkalinity conditions by including carbon in the calculation of the production rates in the same way the nutrients were handled. For low pH conditions carbon limitation can be modeled. The hydrodynamic transport capabilities of CE-QUAL-W2 were used unmodified to calculate the 2-D spatial distribution of constituents within the lake. Changes in pH and the oxidation and precipitation of metals were calculated using the model PHREEQC.

The evolution of the water quality in the lake can be explained by the water fluxes, the reactions in the lake and the erosion and leaching of the bank material. High ground water outflow from the lake is favorable with respect to an effective lake flushing.

Additional Key Words: Pit lake models, surface water flooding
ASSESSMENT OF A TREATMENT SCHEME FOR ACIDIC MINING LAKES USING CO₂ AND CALCIUM OXIDES TO PRECIPITATE CARBONATES

Florian Werner, Bastian Graupner, Broder Merkel, Christian Wolkersdorfer

Abstract. Carbon dioxide and calcium oxides may be used to neutralize acidic lakes. In lignite producing areas combustion power plants producing CO₂ are often close to pit lakes. If fly ashes from these power plants could be used as calcium oxide source, carbonate precipitation in lakes could also as a mineral trap to dispose of CO₂. In a preliminary step the feasibility of this treatment scheme is investigated and includes a model based assessment of expected effects on the surface water, the reactivity of the chemical components, and the technical prerequisites. A pit lake in the Lausitz (Lusatia) post mining area in Germany was chosen as a test site, where fly ash has been deposited for more than 25 years. The feasibility of re-suspending these deposits to neutralize the lake was demonstrated in the years 2000 and 2003, and additional CO₂ is proposed to increase the buffering capacity of the lake water, to precipitate, and store carbonates in the lake sediments.

Additional Key Words: Mineral trapping, lake treatment

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MERCURY DISCHARGES FROM SMALL SCALE GOLD MINES IN NORTH SULAWESI, INDONESIA: MANAGING A CHANGE FROM MERCURY TO CYANIDE

Alfred E. Whitehouse, Harry H. Posey, Tom D. Gillis, Michael B. Long, Asep Atju S. Mulyana

Abstract. Mercury amalgamation is the predominant gold processing method used in North Sulawesi and elsewhere in Indonesia. Only a portion of the mercury used in the process is recovered because floured mercury is discharged directly to upland disposal sites and streams with the tailings and Hg vapor are released when amalgam is heated without retorts to recover gold from amalgam. Cyanide (CN) processing was introduced to recover gold from the tailings so additional Hg vapor is released as the loaded charcoal is burned, breaking the Hg-CN complexes. Small scale gold mines in North Sulawesi alone emit approximately 64 tons of Hg per year to the environment, exceeding the 40 tons per year emitted from coal-fired power plants in the United States.

Replacing Hg-amalgamation with gravity separation followed by vat cyanidation would bring about significant environmental benefits. In this paper we examine some of the more prevalent gold recovery practices in Indonesia, and propose management and beneficiation improvements. We believe these changes would yield higher recovery rates, and would eliminate the environmental damage caused by mercury losses that follow the current processes.

Additional Key Words: mercury amalgamation, cyanidation, mine management
MIXTURES OF WASTE ROCK AND TAILINGS: RESISTANCE TO ACID ROCK DRAINAGE\textsuperscript{1}

Ben Wickland, Ward Wilson, Dharma Wijewickreme, Del Fredlund\textsuperscript{2}

\textbf{Abstract.} The potential for acid rock drainage (ARD) control is examined with respect to the geotechnical properties of mixtures of mine waste rock and tailings. Waste rock, tailings, and mixtures of the same waste rock and tailings were examined for hydraulic conductivity and soil-water characteristic curves through laboratory testing and a meso-scale column study. Both tailings and mixtures had low values of hydraulic conductivity that limit the flow of water and therefore limit the rate of the ARD reaction and the transport of reaction products. Mixtures and tailings were found to have high Air Entry Values (AEV’s) that inhibit the flow of air by maintaining water saturation. In comparison, waste rock was found to have a high value of hydraulic conductivity and a low AEV. The findings demonstrate that mixtures of waste rock and tailings are resistant to acid rock drainage relative to waste rock alone.

\textbf{Additional Key Words:} hydraulic conductivity, soil-water characteristic curve, air entry value

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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PASSIVE TREATMENT OF A CYANIDE AND ARSENIC LADEN PROCESS WATER AT THE RPM GOLD MINE, MINAS GERAIS, BRAZIL

T. R. Wildeman, A.P. Pinto, L.A. Tondo, and L.A. Alves

Abstract: The barren water from a hydrometallurgical process at the RPM Gold Mine averages 100 mg/L of total cyanide, 20 mg/L of arsenic, and has a pH of 9.2. Treatment objectives were to reduce to the total cyanide and arsenic concentration to below 50 and 5 mg/L respectively. The concentration of copper in the water is 50 mg/L suggesting that most of the cyanide exists in the complexed form. A bench-scale passive treatment study was conducted that emphasized the use of common sulfate-reducing bacteria reactors (SRBR) for the elimination of the cyanide. For removal of the arsenic, zero valent iron (ZVI), and native lateritic soils were used in combination with the SRBRs. For total cyanide, the SRBRs reduced the concentrations to below 10 mg/L and those reactors with ZVI reduced the cyanide to an average of 5 mg/L. For arsenic, the SRBRs reduced concentrations to between 1.0 to 6.0 mg/L and the SRBRs with ZVI showed the best removal. The lateritic soils worked well in the beginning to lower the pH and to remove cyanide and arsenic. However, their removal ability became exhausted over the course of the six month study. The results show that a passive treatment system using SRBRs in combination with ZVI would be effective as a primary method for removal of cyanide and arsenic from processing waters

Additional Key Words: Arsenic, cyanide, sulfate-reducing bacteria, zero valent iron, gold processing waters

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LONG-TERM MONITORING OF KIDSTON’S “STORE/RELEASE” COVER SYSTEM OVER POTENTIALLY ACID FORMING WASTE ROCK PILES

David J. Williams, Daniel J. Stolberg and Nicholas A. Currey

Abstract. The rehabilitation of potentially acid forming waste rock is site specific, being a function, among other factors, of the rock types, the dumping and storage method employed, and the climatic setting. The “store/release” cover developed to manage acid rock drainage from mineralized waste rock piles at Kidston Gold Mines’ open pit operations in the semi-arid, seasonal, sub-tropical climate of North Queensland, Australia, has been monitored for nine years. The paper describes the philosophy behind the “store/release” cover design and its adaptation over time to suit Kidston’s conditions. The results of monitoring of a number of covers over the nine years since the first cover was constructed are presented, together with data on seepage flows and water quality emanating from the piles, and estimates are made of the overall water balance of the rock piles. The Kidston story is a valuable case study of a successful approach to remediating an identified source of acid rock drainage in a semi-arid climate, which has actively engaged all Stakeholders.

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PIT BACKFILL: YEA or NAY, A MONTANA EXAMPLE\textsuperscript{1}

R. David Williams\textsuperscript{2}

\textbf{Abstract}: Following a complex legal history after a permit expansion in 1990, a Montana District Court ruled in 2002 that the Golden Sunlight’s reclamation plan must include backfilling the pit in compliance with the Montana State Constitution and the Metal Mine Reclamation Act. The Golden Sunlight Mine submitted a proposed partial pit backfill plan in December of 2002. This presentation will detail the analysis and conclusions of the detailed studies that were undertaken to evaluate the impacts of backfilling the open pit at the mine with 33 million tons of acidic waste rock.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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IRON DYNAMICS IN ACID MINE DRAINAGE

Mark A. Williamson, Carl S. Kirby, J. Donald Rimstidt

Abstract. The oxidation of iron sulfides in mine wastes is the main cause of acidic, sulfate, and trace element-rich acid mine drainage (AMD). However, the suite of reactions that transform iron from one species to another is quite complex. A reasonable strategy for controlling AMD production is to identify and further slow the slowest, rate-determining step (RDS) in the overall process. This paper provides an overall quantitative comparison of iron transformation rates in the AMD process using data from the literature and this comparison allows us to confirm that pyrite oxidation is the RDS for overall acid production over the entire pH range.

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THE APPLICATION OF BLENDED WASTE ROCK AND TAILINGS FOR COVER SYSTEMS IN MINEWASTE MANAGEMENT

G. Ward Wilson, Jozsef Miskolczi, Anne-Marie Dagenais, Isabelle Levesque, Quentin Smith, Lisa Lanteigne, Les Hulett, and David Landriault

Abstract: Waste rock, tailings, and slag from a mine in Sudbury, Ontario were blended to create a material with superior physical and hydraulic properties for the potential construction of a cover system on a large tailings impoundment. The new material, termed Co-Mix, has a low hydraulic conductivity, a high Air Entry Value, and low compressibility. These properties indicate that the Co-Mixed waste rock, tailings, and slag can be used to restrict oxygen entry and water seepage, thus minimizing acid generation and metal leaching within the sulfide bearing mine tailings. The results of laboratory testing for various blend ratios together with soil cover model simulations are used to design a field scale experiment.

Field scale test trials using selected Co-Mix blends of waste rock, tailings, and slag were constructed in October, 2004 at the Copper Cliff mine in Sudbury, Canada. The field scale test trials consist of 5 lysimeters measuring 15x15 m, with a total depth of about 2500 mm. These test trials are currently being used to evaluate the performance of the new material for cover systems that may potentially be constructed on the tailings impoundment upon closure. The lysimeters were constructed with thicknesses of Co-Mix cover material ranging between 600 mm and 1000 mm along with various blend ratios of waste rock, tailings, and slag. The lysimeters will be used to measure seasonal net infiltration rates together with oxygen fluxes to the underlying tailings. The construction of the lysimeter was recently completed and early results with respect to field performance during the spring snow melt period and summer months are presented in this paper for comparison with model predictions.

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HYDROGEOLOGIC CHARACTERIZATION OF GROUND WATERS, MINE POOLS AND THE LEADVILLE MINE DRAINAGE TUNNEL, LEADVILLE, COLORADO\(^1\)

Michael Wireman\(^2\) Jord Gertson\(^2\) Dr. Mark Williams\(^2\)

**Abstract.** The 3385 meter long Leadville Mine Drain Tunnel (LMDT) was completed in 1952 to create a free-draining tunnel to dewater existing and future mine workings in the Leadville Mining District in the Sawatch Mountains of central Colorado. Since 1952 mining has been mostly discontinued in the Leadville district and the physical condition of the LMDT, which discharges approximately 82 l/s, has deteriorated. Roof falls have resulted in blockages which can cause water to pool up, increasing the hydraulic head and presenting a potential blowout problem. Using its’ authority under CERCLA, the US EPA is planning to implement a number of hydraulic and source control elements which are designed to contain and control mine pool water. To support this work the US EPA has completed a rigorous hydrogeologic characterization aimed at developing a sound conceptual understanding of the hydrologic, geologic and geochemical conditions that control inflow of ground water to the underground workings associated with the LMDT and the outflow of mine water from these workings. The investigations discussed here included hydrogeologic mapping, interpretation of water chemistry data and isotopic tracer analysis. The results of this investigation indicate that the LMDT drains only a small volume of mine pool water and a very large volume of regional bedrock and adjacent alluvial ground water. These understandings have been used to design a containment system will be used to control and manage the ground water intercepted by the LMDT and the mine pool(s) that are connected to the LMDT.

**Additional Key Words:** Mining, loading analysis, end-member mixing analysis, isotope hydrology

\(^1\)Paper presented at the 7\(^{th}\) 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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ELEMENT DISTRIBUTION IN WATER AND SEDIMENTS OF AN ACID MINE DRAINAGE DISCHARGE LAKE (pH ~1) OF THE Zn-Pb(-Ag-Bi-Cu) DEPOSIT, CERRO DE PASCO (PERU)\textsuperscript{1}

Christian Wisskirchen\textsuperscript{2}, Bernhard Dold\textsuperscript{3}, Kurt Friese\textsuperscript{4} and Walter Glaesser\textsuperscript{5}

Abstract: A study of an acidic lake (pH ~1) resulting from the deposition of copper leaching spoil waters and acid mine drainage of the Zn-Pb (-Ag-Bi-Cu) deposit Cerro de Pasco is presented. The data shows for the lake water concentration ranges and mean values of 1440-7180 (4330) mg/L Fe, 33.5-105 (87) mg/L Cu, 180-746 (493) mg/L Zn, 13-63 (48) mg/L As, 2.2-5.3 (2.9) mg/L Pb, 11205-42300 (29250) mg/L SO\textsubscript{4}\textsuperscript{2}\textsuperscript{-} and an acidity of 14480-21440 (16775) mg/L CaCO\textsubscript{3}. Lake water mean values did not differ significantly from values measured for discharge water. Within the lake water body most element concentrations increased with water depth.

Infiltrated acidic waters dissolved the limestone bedrock under formation of argillaceous gypsum, overlying dissolving calcite. In the precipitating gel-like matter and upper parts of dissolved bedrock, heavy metals enriched in composition to the lake water. X-ray fluorescence data show for this kind of sediment concentration ranges and mean values of 0.76-12.38 (5.98) wt% Fe\textsubscript{2}O\textsubscript{3}, 51-3980 (1301) mg/kg Cu, 275-8034 (3822) mg/kg Zn, 43-5781 (898) mg/kg As, 21-1310 (261) mg/kg Pb, 0.7-11 (6.2) wt% S. Heavy metals are most likely fixed by organic matter (15 wt% TOC) in form of chelate complexes. The high amounts of organic carbon in the upper part of the sediments most likely results from the discharged spoil waters of the Cu extraction plant. Hydroxides formed during first steps of the infiltration of the bedrock dissolve during later steps of the lake water bedrock interaction.

Additional Key Words: limestone bedrock, copper extraction spoil water, chelate complexes.

\textsuperscript{1}Paper presented at the 7\textsuperscript{th} 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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THE MARINE SHORE PORPHYRY COPPER MINE TAILINGS DEPOSIT AT CHAÑARAL, NORTHERN CHILE

Christian Wisskirchen2 and Bernhard Dold3

Abstract. From 1926 until 1975, the Potrerillos-El Salvador mining district (porphyry copper deposits) sent most of its flotation tailings in suspension through the El Salado River directly to the sea at the Chañaral Bay, Atacama desert, Chile. Over 220 Mt of tailings, containing between 1-2 wt% pyrite, have been dumped into the bay, resulting in a displacement of the shore line over one kilometer further out to the sea. The tailings are estimated to be 10–15 m thick, covering an area of 4.5 km. The hydrology of the tailings system is controlled by a groundwater infiltration of highly saline water (up to 60 g/L Cl and 30 g/L Na) and the tidal cycle. Data suggests that low-saline water (up to 0.9 mg/L Cl and 0.8 mg/L Na), possibly from the municipally water supply or an unknown source, infiltrated into the tailings system. Oxidation resulted in a 70 to 188 cm thick low-pH (0.8 - 4) oxidation zone at the top, which is characterized by jarosite and unidentified orange-brown Fe(III) hydroxides as well as a vermiculite-type mixed-layer mineral as principal secondary mineral assemblage. The oxidation zone is underlain by a neutral primary zone. Mineralogical and hydrogeochemical data indicate, that the bivalent metal cations as Cu, Ni and Zn are liberated in the oxidation zone (up to 2265 mg/L, 18.1 mg/L and 20.3 mg/L, respectively). They are mobile under acidic conditions and are transported towards the tailings surface via capillary processes. These processes led to metal enrichment at the tailings surface (e.g. up to 2.4% Cu) in form of secondary chlorites or sulfates (dominated by eriochalcite [CuCl2·H2O] and halite). These secondary minerals are mainly water-soluble and exposed to eolian transport towards the village of Chañaral. Data from sequential extraction show that Cu is present in the beach area (between 1000 and 2000 mg/kg) mainly in the exchangeable (“adsorbed”) fraction. This suggests that when the acid metal-rich solutions from the oxidation zone are in contact with the marine water during the tidal cycle, bivalent cations became adsorbed and their transport in the seawater seems mainly to be associated with particles in suspension. The transport direction seems to be laterally toward the sea during low tide. But also at neutral pH conditions in the lower part of the primary zone (3-7 m depth), Cu and Zn mobility is observed (up to 19 mg/L and 12 mg/L, respectively) associated with the highly saline waters, most probably as chloro complexes. In contrast to the bivalent cations, oxyanions as As and Mo are below detection limit in the pore water of the low-pH oxidation zone due to adsorption to secondary Fe(III) hydroxides, shown by sequential extractions. Below, in the saturated neutral zone, high concentrations of As and Mo were encountered with up to 608 and 10266 µg/L, respectively. The residual concentrations of As in the tailings at the surface, which are exposed to eolian transport, are between 14 and 61 mg/kg mainly associated to the Fe(III) hydroxide fractions.

Two element flow directions (towards the tailings surface via capillarity and towards the sea) and two element groups with different geochemical behavior (cations such as Cu, Zn, Ni and oxyanions such as As and Mo) can be differentiated. It can be postulated, that the sea is mainly affected by As, Mo, Cu, Zn contamination by seepage form tailings and the El Salado River, while the population of Chañaral is mainly exposed to high concentrations of Cu and minor Ni and Zn via eolian transport in form of water-soluble secondary mineral particles.

Additional Key Words: Copper, Arsenic, tidal influence, high saline water, eolian transport, bioavailability

1Paper 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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ACID MINE DRAINAGE TRACER TESTS

Christian Wolkersdorfer

Abstract. Acid mine drainage, the drainage of metals, and the prediction of mine water rebound after mine closure are major problems for the mining industry. In the literature, the difficulties in evaluating the hydrodynamics of flooded mines are well described, although only a few tracer tests in flooded mines have been published. Increased knowledge about the hydraulic behaviour of the mine water within a flooded mine might significantly reduce the costs of mine closure and remediation. Relatively cheap and reliable results for decision making can be obtained when tracer tests are properly conducted in a flooded mine prior to planning of remediation strategies or numerical simulations. Applying the results of successful tracer tests allows one to optimise remediation designs and thereby diminish the costs of remediation. The paper summarises the results of several tracer tests and draws general conclusions from such tests.

Additional Key Words: mine water, flooded shaft, underground mining, mine water pollution

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CREATING WETLANDS FOR COMPENSATORY MITIGATION BY RECLAMATION OF IRON MINE TAILINGS BASINS AT THE REPUBLIC MINE IN MARQUETTE COUNTY, MICHIGAN¹

R.D. Workman, M.P. Owens, C.L. Wolverton, G.J. Goodman²

Abstract. Iron mining in Michigan’s Upper Peninsula has unavoidably impacted regulated wetlands. State and federal laws require these wetland impacts be mitigated by the creation or restoration of compensatory wetlands. Integrating wetland creation with tailings basin reclamation provided the necessary wetland acreage for regulatory compliance. The properties of the tailings and the design of the basins provided not only a suitable medium and location for wetland creation, but also presented substantial challenges. The creation of new wetlands required manipulation of the water levels within the basins and careful wetland design. Michigan Department of Environmental Quality permits required creating emergent, scrub/shrub, and forested wetland communities on neutral tailings. Numerous planting and seeding techniques were used to establish the different plant communities. These techniques included dormant seeding, drill seeding, aerial seeding, and transplanting wetland vegetation. Cover crops of Japanese millet (Echinochloa crusgalli) and red-top grass (Argrostis alba) were used in conjunction with hay mulch minimize erosion and sequester wind blown seeds from the surrounding native areas. Forested wetlands were established by transplanting wetland tree species at specific tree densities to compensate for expected mortality. The established wetland communities were monitored annually for a period five years to document the successful development of vegetation, hydrology, and wildlife in accordance with reclamation success criteria.

Additional Key Words: replacement wetlands, mitigation, tailings reclamation, revegetation, restoration techniques.

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REMEDIATION OF GROUNDWATER CONTAMINATED WITH ZN, PB AND CD USING A PERMEABLE REACTIVE BARRIER WITH APATITE II

Judith Wright and James L. Conca

Abstract. Phosphate-Induced Metal Stabilization (PIMS) using 100 tons of the reactive media, Apatite II™ \(\text{Ca}_{10-x}\text{Na}_x(\text{PO}_4)_{6-x}(\text{CO}_3)_x(\text{OH})_2\) where \(x < 1\), was used in a permeable reactive barrier (PRB) to treat shallow alluvial groundwater from acid mine drainage. The groundwater is treated \textit{in situ} before it enters the East Fork of Ninemile Creek, a tributary to the Coeur d’Alene River. Microbially-mediated sulfate reduction and the precipitation of sphalerite (ZnS) is the primary mechanism occurring for immobilization of Zn and Cd. Precipitation of pyromorphite \(\text{Pb}_{10}(\text{PO}_4)_{6}(\text{OH,Cl})_2\) is the most likely mechanism for immobilization of Pb. Precipitation occurs on the original Apatite II grains. Emplaced in January of 2001, the PRB has continuously reduced the concentrations of Cd and Pb about 1 mg/L to below detection (2 mg/L), has reduced Zn to less than 0.1 mg/L, and has reduced sulfate and nitrate to below 0.05 mg/L, removing about 10,000 lbs of Zn, 200 lbs of Pb, and 100 lbs of Cd. About 90% of the immobilization is occurring in the first 20% of the barrier with loadings up to 25% Zn by weight of Apatite II.

Additional Key Words: phosphate, acid mine drainage.

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\(^1\) Poster paper presented at the 7\textsuperscript{th} 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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INNOVATIVE WATER TREATMENT PLANT UTILIZING THE SOUTH MINE PIT AT THE COPPER BASIN MINING SITE IN TENNESSEE, USA

Griff Wyatt, Franklin Miller, John Chermak

Abstract. To protect the Ocoee River in Tennessee (USA) from acidity and metals loadings from historical copper mining and processing activities, OXY USA is conducting removal actions to alleviate contaminant discharges from North Potato Creek (NPC). One such action is construction of an innovative in-pit lime treatment facility at the South Mine Pit designed to treat NPC flows up to a 10-yr, 24-hr storm of 1,649 m³/min (972 cfs) prior to discharge to the Ocoee River.

OXY USA performed an Engineering Evaluation / Cost Analysis (EE/CA) to identify and evaluate alternatives to address contaminant discharges from North Potato Creek to the Ocoee River. The alternative that was determined to best meet the evaluation criteria was the in-pit treatment alternative. The in-pit treatment system treats the entire 10-yr, 24-hour storm flow of NPC by adding lime to raise the pH to the level required to precipitate dissolved metals and then settling the precipitated solids in an existing 8.1 hectare (20 acre) abandoned surface mine pit. The treatment system utilizes the existing surface mine pit as a settling pond. The in-pit treatment facility was constructed for 15% of the estimated cost of a conventional lime treatment facility capable of treating comparable NPC flows. The NPC Water Treatment Plant operations began in January 2005 and results show that reductions in aluminum, copper, iron, manganese, zinc, and other dissolved metals loading of over 360 kg (790 lbs.) per day to the Ocoee River are being achieved.
NET ACID PRODUCTION, ACID NEUTRALIZING CAPACITY AND ASSOCIATED GEOPHYSICAL, MINERALOGICAL, AND GEOCHEMICAL CHARACTERISTICS OF ANIMAS RIVER WATERSHED ROCKS, SILVERTON, COLORADO

Douglas B. Yager, Anne McCafferty, Mark R. Stanton, Sharon F. Diehl, and Rhonda L. Driscoll

Abstract. This report presents results from laboratory studies involving the net acid production (NAP), acid neutralizing capacity (ANC), and magnetic mineralogy of thirty-four samples collected in the Upper Animas River watershed near Silverton, Colo., during the summer of 2003. Sampling focused mainly on the volumetrically important, Tertiary-age volcanic and plutonic rocks that are host to base and precious metal mineralization in the study area.

Rocks in the study have all been subjected to a regional propylitic alteration event that modified the primary mineralogy of the host rock, while introducing minerals with acid neutralizing capacity (ANC) including calcite, chlorite and epidote. Locally, hydrothermal alteration has removed any ANC and introduced minerals, mainly pyrite, that has a high net acid production (NAP). Laboratory studies included hydrogen peroxide (H₂O₂) acid digestion and subsequent sodium hydroxide (NaOH) titration to determine NAP, and H₂SO₄ acid titration experiments to determine ANC on selected samples that generally had low NAP. In addition to these environmental rock property determinations, mineralogical, chemical, and petrographic characteristics of each sample were determined through multiple methods including semi-quantitative X-ray diffractometry (Rietveld method), optical mineralogy, wavelength dispersive X-ray fluorescence, total carbon-carbonate, and 40-element inductively coupled plasma analyses. Magnetic susceptibilities, converted to estimates of volume-percent magnetite were also calculated. Although magnetite is a minor mineral constituent, it is easily measured, and can be positively correlated to measurable percentages of important acid-neutralizing minerals, such as chlorite and calcite and inversely correlated to NAP indicator minerals including pyrite and clay minerals.

Ranks were assigned to the samples based on ANC quantity in kg/ton calcium carbonate equivalent, and ratios of ANC to NAP. Results show the Pyroxene Andesite Member of the Silverton Volcanics has highest ANC with little to no NAP in either the propylitic or weakly sericitically-altered samples. Samples of the propylitically altered Pyroxene Andesite Member also contains the highest mean magnetite abundance (over 8 volume percent) and therefore, may permit its regional mapping using the airborne magnetic and electromagnetic survey data. The Burns Member of the Silverton Volcanics samples, in general have a low ANC, high to moderate NAP, and in general, contain little to no magnetite. Samples containing sparse pyrite (≤ 1 weight percent) have NAP that ranges from non-detectable to 39 kg/ton CaCO₃. Samples with no detectable calcite often contain abundant chlorite species (clinochlore and chamosite).
Acid titration was performed on a chlorite mineral separate comprised mainly of the minerals clinochlore and chamosite, collected from a Burns Member lava with a high ANC (second highest ANC of all samples studied) and that lacks calcite. Acid titration results indicate that chlorite species have some ANC over a range between pH 4 and pH 2. The calculated ANC of the chlorite mineral separate is 54 kg/ton CaCO$_3$ equivalent. This indicates that samples that lack calcite, where chlorite is also abundant could supply some ANC.

This study provides information that could prove useful to local stakeholders groups, federal land managers, and others involved in mine cleanup efforts. Several samples studied have ANC values that exceed the 20 kg/ton CaCO$_3$ equivalent necessary for consideration in mine waste remediation treatments. Thus, data collected for the environmental rock properties, NAP and ANC, of Animas River watershed rocks could aid in locating rocks that could be suitable for testing in ongoing mine waste remediation efforts.

**Additional Key Words:** propylitic alteration, volcanic rocks, Silverton Volcanics, airborne magnetic and electromagnetic survey, magnetic mineralogy, chlorite

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2 Douglas Yager is a geologist, Anne McCafferty a geophysicist, and Mark Stanton a geologist with the U.S. Geological Survey, Denver, CO, 80225. Sharon Diehl and Rhonda Driscoll are both geologists with the U.S. Geological Survey in Denver, CO.
PREDICTIONS AND REALITY: GENERATION OF STRONGLY NET-ACIDIC MINE WATERS THROUGH FLOODING OF UNDERGROUND COAL MINE WORKINGS WITH LIMESTONE ROOF STRATA, BLENKINSOPP COLLIERY (NORTHUMBERLAND, UK)¹

Paul L. Younger² and Peter Thorn³

Abstract. Blenkinsopp Colliery (Northumberland, UK) was the second-last underground coal mine in production in the former Great Northern Coalfield of England. The immediate roof beds of the single worked seam included a thick limestone bed; an unusual occurrence in UK coal mines. Hydrogeochemical investigations of the water encountered underground during the working of the mine revealed that specific qualities of water were logically related to details of the flowpaths the waters were inferred to have taken to reach the accessible sampling points. Working from this information, and taking into account observations of mineralogical and mining engineering aspects of the workings, a conceptual model was developed which assisted in predicting the likely response of the colliery to abandonment and flooding. In particular, it was predicted that, despite the presence of limestone in the roof and in goaf materials, the early outflows from the mine would be sufficiently acidic that they would require active treatment. Flooding of the mine is now complete, and post hoc analyses have largely vindicated earlier predictions of the time it would take for the mine to flood to surface, and the approximate post-flooding flow rates. The prediction that the water would be strongly net-acidic has also been borne out by observations: it is clear that the presence of limestone in a mined sequence is no guarantor of a neutral-pH discharge. However, the extremely high iron concentrations encountered post-flooding (≤ 1000 mg/l Fe⁺²) have exceeded expectations by a factor of around 3.3. Improvement in the understanding of likely quality, perhaps by means of tracer tests in recently flooded workings, could help reduce risks related to treatment scheme design, thus enabling more robust design and budgeting to be carried out as early as possible in the post-closure management period.

Additional Key Words: acidity, coal, limestone, mine, prediction, water, UK.

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Abstract. The European Directive on Groundwater (80/68/EEC) was fully transposed into Scottish law by the introduction of the Groundwater Regulations 1998. These Regulations forbid the introduction of certain substances (denoted as "List I substances") into groundwater, and also place limitations on the extent to which other substances ("List II substances") may be permitted to enter groundwater. Scottish opencast mining, which constitutes an ‘activity’ under the terms of the Groundwater Regulations, poses little risk of introducing List I substances into groundwater, but it has substantial potential to lead to the migration of several 'List II' substances. Accordingly, the Scottish Environment Protection Agency (SEPA) commissioned an assessment framework for pollution prevention in opencast coal mining. The development of the framework was founded upon a comprehensive critical review of the literature on acidic drainage prediction, from which it emerged that there has been an excessive concentration on simple pollution potential assay tests (acid-base accounting, humidity cell tests) at the expense of rational assessments of contaminant transport pathways. The new Framework described here rectifies this imbalance, emphasising the over-arching importance of developing a robust site conceptual model, which is progressively refined as relevant data (mineralogical, geochemical, hydrological) become available. The conceptual model then provides the basis for risk assessment and impact mitigation planning.

Additional Key Words: acid-base accounting, acidity, coal, conceptual model, guidelines, groundwater, humidity cell test, opencast, prediction, Scotland.
PARTNERSHIP FOR ACID DRAINAGE REMEDIATION IN EUROPE (PADRE): BUILDING A BETTER FUTURE FOUND ON RESEARCH AND BEST PRACTICE.¹

Paul L. Younger² Christian H. Wolkerdorfer, Rob J Bowell and Ludo Diels

Abstract. PADRE has been established as a permanent commission of the International Mine Water Association (IMWA), with the aim of fostering best practice, based on the latest research, in the remediation of acidic drainage from active and abandoned mine sites throughout Europe. PADRE activities include: maintaining best practice guidelines on passive remediation (the PIRAMID Guidelines) and catchment-scale mine water management (the ERMITE Guidelines); developing further sources of guidance; implementing training and professional development activities for European scientists and engineers (not least through the CoSTaR facility); and acting as the European branch of the Global Alliance convened by INAP.

Additional Key Words: acidity, best practice, Europe, guidelines, INAP, mining, training.

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A MODULAR FIELD-BIOREACTOR FOR ACID ROCK DRAINAGE TREATMENT

Marek H. Zaluski, Diana R. Bless, Linda Figueroa, Helen O. Joyce

Abstract. The paper focuses on the improvements to engineered features of a passive technology that has been used for remediation of acid rock drainage (ARD). This passive remedial technology, a sulfate-reducing bacteria (SRB) bioreactor, takes advantage of the ability of SRB that, if supplied with a source of organic carbon, can increase pH and alkalinity of the water and immobilize metals by precipitating them as metal sulfides or hydroxides.

The remoteness of ARD sites and their abundance require that the design of an SRB bioreactor be simple and inexpensive. Therefore, bioreactors need to be designed to a size that allows for transportation using primitive roads. To satisfy these requirements a design for a modular treatment system was developed using reactive cartridges (RC) that are prefabricated as 2.44-meter diameter vessels. The RC has been designed so it supports the prime functional aspects of a bioreactor such as high permeability, ample supply of organic carbon, ability to maintain anaerobic conditions, and capacity to accumulate precipitated metals and means for their periodic removal, as needed. In addition, the configuration of the RC allows for an easy replacement of the organic carbon. The RCs can be transported to an ARD site and assembled into a treatment system with a number of modules as required by the ARD flow rate and the metals load. A bioreactor system consisting of four RCs will be installed at an abandoned mine site with ARD of pH 5 or lower and a significant load of metals. The process of site selection is in progress.

The RC design was developed by the Mine Waste Technology Program (MWTP) at MSE Technology Applications (MSE), Butte, Montana, USA. The work was funded by the U.S. Environmental Protection Agency (EPA) and was jointly administered by the EPA and the U.S. Department of Energy (DOE) National Energy Technology Laboratory and performed at the Western Environmental Technology Office under DOE contract number DE-AC09-96EW96405.

Additional Key Words: cartridge, walnut shells, corn stover
THE EVOLUTION OF EVAPOTRANSPIRATION COVER SYSTEMS AT BARRICK GOLDSTRIKE MINES

Guosheng Zhan, William Schafer, Mike Milczarek, Ken Myers, Joe Giraudo, and Ron Espell

Abstract. Barrick Goldstrike Mines Inc. (BGMI) has developed a comprehensive closure planning, materials characterization and in-situ monitoring program for the closure of its mine waste facilities. Facility closure techniques use topsoil and in-pit material to construct evapotranspiration (ET) cover systems to reduce or eliminate infiltration of meteoric water. One major facility at BGMI, the AA Leach Pad (AA Pad) has been closed. The Bazza Waste Rock Facility (WRF), which will hold about 1.75 billion metric tonnes (mt) of waste rock within an area of 950 hectares (ha), is undergoing concurrent closure over the next 10 years. Hydrologic performance of the AA Pad cover and the inventory, suitability and timing of in-pit materials dictated the ET cover design approach for the Bazza WRF.

The AA Pad ET cover system was constructed in 2000 using two comparative cover systems; 1.2 m of fine-grained Tertiary-aged valley fill deposits of the Carlin formation, and 1.5 m of salvaged topsoil materials. The flux of meteoric water through the AA Pad cover was measured using in-situ vadose zone monitoring. Both covers had very low deep percolation rates, especially after vegetation matured. The AA Pad monitoring results were used to optimize the Bazza cover. First, an unsaturated flow model was calibrated to the in-situ monitoring data from the AA Pad. Next, the hydraulic properties of cover materials to be used for the Bazza cover were determined in large-diameter cores to minimize scale effects. Large scale in-situ hydraulic testing was also conducted to assess material variability. Finally, in-situ monitoring systems were installed in concurrent reclamation areas at the Bazza WRF.
DISPOSAL, REPROCESSING AND REUSE OPTIONS FOR ACIDIC DRAINAGE TREATMENT SLUDGE¹

Janice Zinck²

Abstract: Sludge management is an escalating concern as the inventory of sludge continues to grow through perpetual “pump and treat” of acidic waters at mine sites. Current sludge management practices, in general, are ad hoc and frequently do not address long-term storage, and in some cases, long-term stability. While a variety of sludge disposal practices have been applied, many have not been fully investigated and monitoring data on the performance of these technologies is limited and not readily available. This paper discusses options for treatment sludge management including conventional disposal technologies, reprocessing options for metal recovery, novel sludge reuse technologies and options for reclamation of sludge areas.

Additional Key Words: lime treatment, high density sludge process, co-disposal, sludge stability, pond disposal, backfill, leaching, mine reclamation

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UTILIZING INDUSTRIAL WASTES AND ALTERNATIVE REAGENTS TO TREAT ACIDIC DRAINAGE¹

Janice Zinck² and Wesley Griffith²

Abstract: Waste by-products from various industries can be successfully applied to treat acidic drainage. The advantages of utilizing waste material for treatment of other wastes include cost savings, greenhouse gas reduction (from lime) and reduced waste management requirements. Several waste products and their treatment effectiveness were evaluated. The performance of papermill sludge, cement kiln dust (CKD), lime kiln dust (LKD), and calcium magnesium hydrate (CMH) were assessed in terms of treatment efficiency and environmental performance. This study found that these alternative reagents could be used to replace lime in mine water treatment. Significant greenhouse gas (GHG) and reagent cost savings could be realized if lime was replaced with ‘waste’ or alternative low cost reagents.

Additional Key Words: lime treatment, high density sludge process, cement kiln dust, lime kiln dust, papermill sludge, calcium magnesium hydrate, climate change, greenhouse gas emissions

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