

**METHODS FOR DELAYING
THE ONSET OF ACIDIC
DRAINAGE - A CASE STUDY
REVIEW
FINAL REPORT**

MEND Project 2.37.2

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METHODS FOR DELAYING THE ONSET OF ACIDIC DRAINAGE
A CASE STUDY REVIEW

FINAL REPORT
MEND 2.37.2

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Scientific Authority: Gilles A. Tremblay

555 Booth St.

Mining & Mineral Sciences Labs

Ottawa, ON K1A 0G1

Prepared by:

STEFFEN ROBERTSON AND KIRSTEN (CANADA) INC.

Suite 800, 580 Hornby Street

Vancouver, B.C. V6C 3B6

Tel: (604) 681-4196 • Fax: (604) 687-5532

E-mail: www.srk.com

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EXECUTIVE SUMMARY

Several methods to delay the onset of acidic drainage have been tested:

- bactericide application;
- deposition in permafrost;
- phosphate application; and
- irrigation with alkali,

Other methods have been applied as permanent controls but could be designed as delays:

- simple soil covers;
- oxygen-consuming organic covers;
- blending; and
- lime application,

Information about each of the above methods was collected from literature and from interviews with mine operators and researchers. A brief overview of each method is presented, and case histories are described. The extent to which the case histories prove the effectiveness of each method is reviewed.

In general, the review concludes that there is a lack of well-designed and documented studies of methods to delay the onset of acidic drainage. However, several of the reviewed methods are promising enough to warrant further research. A well-designed field study of bactericides is needed to demonstrate whether this method can be effective in metal mine waste. Alkali addition and soil covers are clearly effective for dealing with waste that is already acidic, but their effectiveness as delay methods needs to be demonstrated. Organic oxygen-consuming covers have been shown to be effective for tailings but still need testing on waste rock. Low temperatures have been shown to slow ARD, but further work is needed to quantify the benefits and investigate possible difficulties associated with depositing waste into a permafrost setting.

A list of general requirements for such studies is presented. The review also provides specific recommendations for studies of each method.

SOMMAIRE

On a testé plusieurs méthodes permettant de différer le drainage acide :

- application de bactéricide;
- déposition dans le pergélisol;
- application de phosphate; et
- irrigation avec un alcali.

D'autres méthodes appliquées comme mesures de prévention permanente pourraient aussi être qualifiées de mesures de retardement :

- couvertures simples à partir de matériaux meubles d'origine naturelle;
- couvertures organiques consommateurs d'oxygène;
- mélange; et
- épandage de chaux.

Les renseignements sur chacune des méthodes susmentionnées ont été obtenus dans la littérature et lors d'entretiens avec des opérateurs miniers et des chercheurs. On présente un bref aperçu de chaque méthode et on décrit des exemples typiques. On examine dans quelle mesure ces exemples permettent d'établir l'efficacité de chaque méthode.

En général, on en arrive à la conclusion que peu d'études bien conçues et documentées ont porté sur les méthodes permettant de différer le drainage acide. Toutefois, plusieurs des méthodes examinées semblent suffisamment prometteuses pour justifier la poursuite des recherches dans ce domaine. Il faudra effectuer sur le terrain une étude bien conçue sur les bactéricides pour établir si cette méthode peut être efficace dans le cas des déchets de mines de métaux. L'addition d'un alcali et l'application d'une couverture en sol sont de toute évidence des méthodes efficaces pour traiter les déchets déjà acides, mais leur efficacité en tant que méthodes de retardement reste à démontrer. On a montré que les couvertures organiques consommateurs d'oxygène sont efficaces dans le cas des résidus miniers, mais d'autres tests devront être effectués dans le cas des stériles. Le drainage acide est plus lent à basse température; cependant, il faudra effectuer d'autres travaux pour en quantifier les avantages et déterminer les difficultés possibles de la déposition des déchets miniers dans le pergélisol.

On présente une liste des exigences générales pour de telles études. On formule aussi des recommandations spécifiques sur les études qui porteront sur chaque méthode.

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**METHODS FOR DELAYING THE ONSET OF
ACIDIC DRAINAGE – A CASE STUDY REVIEW**

1.0 INTRODUCTION

1.1 Terms of Reference

The objective of the project reported herein was to review methods for delaying the onset of acidic drainage and metal discharge from mine rock, and, in particular, to compile case histories from mine sites where the delay of acid rock drainage has been assessed or attempted.

The Mine Environment Neutral Drainage (MEND) Program contracted Steffen Robertson & Kirsten (Canada) Inc. to carry out the review. The project was sponsored by the BC Ministry of Employment and Investment, Energy and Minerals Division, and the Canada Centre for Mineral and Energy Technology (CANMET) through the Canada/British Columbia Mineral Development Agreement.

1.2 Background

At many mine sites, waste must be stored temporarily before final disposal. For example, the mine plan may call for backfilling of an open pit in which mining has not yet been completed. At other sites, waste may be deposited at its final location, but long term control measures such as flooding or covering can only be implemented at a later date. In these cases, it is desirable to find methods for delaying the onset of acidic drainage.

Among the methods that have been used or tested to delay the onset of acidic drainage are:

- bactericide application;
 - deposition in permafrost;
 - phosphate application; and,
 - irrigation with alkali.
-

Other measures that have been applied as permanent controls could be designed as delays. Examples include:

- simple soil covers;
- oxygen-consuming organic covers;
- blending;
- lime application; and,
- layering of waste rock.

The blending or layering of acid generating material with acid-consuming rock are addressed in a separate document, MEND Report, 2.37.1, Blending and Layering Waste Rock to Delay, Mitigate or Prevent Acid Generation – A Case Study Review.

1.3 Method of Data Collection

An initial teleconference was held with representatives from SRK, MEND and selected experts. The teleconference clarified the objectives of the review and identified temporary control measures and locations where they have been planned or applied. The discussion resulted in a list of locations that could be used as possible case studies. Minutes from the teleconference are provided in Appendix A.

Information was collected by telephone, facsimile and electronic mail from contacts in the mining industry, government organizations, research organizations and consulting firms in Canada, the United States, Sweden, Australia and New Zealand. Information available in the literature was used as background. Organizations contacted are listed in Table 1.1. Delay methods and case study locations are listed in Table 1.2. Information available in scientific journals and conference proceedings was used as background.

1.4 Report Organization

Individual methods for delaying the onset of ARD are presented in Chapters 2 through 8. Each chapter describes a method, one or more case histories and a discussion of the results. Chapter 9 provides a brief overview and recommendations for future work.

TABLE 1.1
Organizations Contacted

Canterbury Coal Company	Morwijk Enterprises
MV Technologies	ADI Nolan Davis & Associates
Boojum Research	Schafer & Associates
National Research Centre for Coal and Energy	Minnesota Department of Natural Resources
Pennsylvania Department of Environmental Protection	Australian Centre for Minesite Rehabilitation
CANMET	PT Kelian Equatorial Mining
Swedish Environmental Protection Agency	Environmental Geochemistry International
State of South Dakota	Boliden AB
Voisey's Bay Mine Ltd.	Brohm Mining
Inco Ltd.	University of Saskatchewan
University of Western Ontario	Equity Silver Mine
Westmin Resources Ltd.	Golden Sunlight Mine
New Brunswick Coal Ltd.	Lac Minerals
Heath Steele Mines	Lakefield Research
Action Mining Company	University of Stockholm
US Bureau of Mines	Terratema AB
Power & Water Authority, Australia	Noranda Technology Centre
Anchor Energy	Homestake Mining Company
CRA ATD	Princeton Mining Corporation
C.E. Jones & Associates	Québec Ministry of Natural Resources
Glenn Springs Holdings Inc.	University of Kentucky
Ohio Department of Mines and Reclamation	

TABLE 1.2
Case Study Locations for Delay Techniques

Technique	Study Location
Bactericides	Route 43, East Springfield, Ohio
	Cover Hill, Meyersdale, Pennsylvania
	A silver mine, Idaho
	Equity Silver, Houston, BC
	Branchton Disposal Site, Butler County, PA
Phosphate Application	n/a
Alkali Addition	Stratmat, Heath Steele Mine, NB
	Fire Road Mine, Minto, NB
Low Permeability Covers	Bersbo Mine, Sweden
	Equity Silver, Houston, BC
	Pile 7/12, Heath Steele Mine, NB
Freezing	n/a
Inorganic Oxygen-Consuming Layer	Ronneburg Uranium Mining District, Germany
Organic Oxygen-Consuming Layer	East Sullivan Mine, Val d'Or, PQ
	Laboratory program

2.0 BACTERICIDE APPLICATION

2.1 Description

At pH below 5, sulphide oxidation can be enhanced by bacteria that catalyse the oxidation of ferrous (Fe^{2+}) iron. The bacteria, of which *Thiobacillus ferrooxidans* is the most common, can be inhibited by the use of bactericides. The most commonly referenced bactericides are surfactants, such as sodium lauryl sulphate or sodium dodecylbenzine sulphonate. Tests of other bactericides/fungicides, such as potassium benzoate and potassium sorbate, have also been reported. The surfactants reportedly alter the protective greasy coating that protects the bacteria from the low pH environment, and/or disrupt the contact between the bacteria and the mineral surface. No clear reference was found to explain the method by which the bactericides/fungicides function.

Bactericides have been applied to waste piles as a slurry sprayed on the pile and as a powder mixed with the waste during pile construction. However, bactericides are easily washed from the rock or break down over time, requiring reapplication every 3 to 6 months. Therefore, bactericides are now most commonly applied in time-release pellets that continue to release surfactants for seven years or longer (Kleinmann *et al.*, 1981; Rastogi, 1995; Environmental Management, 1995).

2.2 Case Histories

2.2.1 Route 43, Ohio

The Ohio Department of Natural Resources undertook the reclamation of an abandoned coal refuse pile in 1984. The pile, dubbed the Route 43 site, is located near East Springfield, Ohio. The pile was triangular in shape with an area of approximately 2 ha and a height of 15 m. The site had been abandoned since 1960. No amendments were applied to the pile prior to 1984.

Initial characterization of the pile indicated that the paste pH of the refuse was less than 3.0 across the site while the pH of 10:1 water:refuse extracts ranged from 2.5 to 3.5. Sulphur analysis on the refuse showed 1.32% total sulphur, 0.11% sulphate sulphur, 0.43% pyritic sulphur and 0.78% organic sulphur (Splittorf *et al.*, 1995 and Sobek *et al.*, 1990). No neutralization potential measurement was made (Sobek *et al.*, 1990).

The refuse pile was recontoured and divided in two from the apex of the triangle to the base, past which a stream flowed. The upstream half of the pile was designated the control side and the downstream half was treated with bactericides. The bactericide application consisted of 225 kg/ha of 88% active bactericide powder applied as a water based solution and 575 kg/ha of controlled release bactericide containing 16 - 28% active ingredient. A proprietary treatment system was used.

After the bactericide application, both the treated and control sides were covered with 15 to 20 cm of topsoil obtained from a borrow source adjacent to the site. Topsoil covering began at the base of the pile and moved towards the apex, covering both the treated and control sides simultaneously. 336 kg/ha of 16-16-16 fertilizer and 6.9 metric tonnes (mt)/ha of lime was added to the topsoil. Both sides were seeded with 61.6 kg/ha of seed mixture then covered with 4.5 mt/ha of hay mulch (Splittorf *et al.*, 1995).

The site was monitored on an annual basis from 1985 to 1989 and three times in 1994 (Sobek *et al.*, 1990). The monitoring program consisted of eight pressure-vacuum lysimeters to measure moisture content, a rain gauge, an evaporation pan, water sampling, soil sampling to measure the most probable numbers of *T. ferrooxidans* and other heterotrophic bacteria, and photographic documentation. A detailed description of the methods is provided in Sobek *et al.*, 1990.

Measured values were obtained for the microbiology, water quality and biomass. The ratios of *T. ferrooxidans* to heterotrophs (i.e. bacteria that utilize organic carbon) for both the treated and control areas are presented in Table 2.1.

TABLE 2.1
Ratio of T. Ferrooxidans to Heterotrophic Bacteria Over Ten Years
(Splittorf *et al.*, 1995.)

	1985	1986	1987	1988	1989	1994
Bactericide treated	0.05	0.35	0.22	0.25	0.43	1.4×10^{-4}
Control	70	10	1000	1.2	41	2×10^{-4}

Water quality samples were collected from drains on a monthly basis between 1985 and 1989. A water sample was collected from the control side of the refuse pile in June 1994. The seepage drain from the treated side was dry during the three site visits made in 1994. Table 2.2 summarizes the percentage of metal reduction in the treated side compared to the control side from 1985 to 1988.

TABLE 2.2
Comparison of Treated and Untreated Areas (Sobek *et al.*, 1990).

Parameter	Year			
	1985	1986	1987	1988
Acidity	72%	58%	97%	89%
Specific Conductivity	35%	32%	67%	86%
Total Iron	52%	73%	92%	99.6%
Manganese	94%	91%	44%	16%
Aluminum	93%	89%	99.5%	99%
Sulphates	68%	58%	81%	57%

Table 2.3 provides the water quality data from the drains in 1989 and 1994. The data indicate that the water quality exiting the refuse pile improves over time even without the use of bactericides. This is seen when comparing the 1989 and 1994 water quality data from the control side. (The sulphate value of 9 mg/L appears to be erroneous. The reported conductivity would be more consistent with a sulphate concentration in the hundreds of mg/L.) Despite the water quality improvement on the control side, the treated side in 1989 still had better water quality.

TABLE 2.3
Water Quality from Drains (Splittorf *et al.*, 1995)

	pH	Cond. (μ mhos)	Acidity (mg eq/L)	Sulphate (mg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)
1989 – treated	5.9	590	19	100	0.2	0.3	0.5
1989 – control	2.6	2910	844	2040	104	6.1	38.7
1994 – control	3.4	851	112	9	16	1.6	9.3

Biomass production was determined by harvesting the vegetation from six 1m x 1m plots, three plots on the treated side and three plots on the control side. The samples were dried and weighed. The data obtained in 1989 and 1994 are presented below in Table 2.4. The biomass production for the control side is expressed as a range due to the large areas without vegetation. The data suggest that the bactericide encouraged a favourable microenvironment in the soil for a sufficient time period that vegetation could be established. From the results obtained, it appears that the bactericide “leapfrogs” by several years the natural process of establishing vegetation.

TABLE 2.4
Comparison of Biomass Yield (Splittorf *et al.*, 1995)

Biomass Yield (kg/ha) in 1989		Biomass Yield (kg/ha) in 1994	
Treated Side	Control Side	Treated Side	Control Side
2915	0 to 315 max	4118	0 to 1895 max

Photographs were taken of the site in 1987 and 1994. Both sets of photos showed higher density and higher quality vegetation on the bactericide treated side of the refuse pile. The drain and surrounding area on the control side was observed to have iron staining. In 1994, the control side was predominantly barren with a significant amount of erosion.

2.2.2 Cover Hill Mine, Meyersdale, Pennsylvania

Bactericides were used to delay acid generation at the Cover Hill Mine in Meyersdale, Pennsylvania. The mine was located on a coal seam that had caused local acidic drainage problems. The Coal Hill deposit was mined as a continuously advancing open pit. As one face of the pit was mined, waste was deposited at the back of the pit and covered. There was some time delay before the spoil pile was covered. To prevent the development of acidic drainage during this period, approximately 0.15 g bactericide, containing 88% active ingredient, was sprayed onto the spoil pile for every kilogram of waste. After the spoil pile was covered and recontoured, controlled release bactericide pellets containing 28% active sodium dodecylbenzene sulfonate were added at the rate of 785 kg/surface ha. The surface was then covered with subsoil and topsoil and revegetated (Parisi, *et al.*, 1994).

Two years after mining and reclamation were completed, no acid generation has been detected. However, no control sites were established and the pit floor and some of the

overlying backfill was composed of limestone. Therefore, it is difficult to determine whether the lack of acidic drainage resulted from the bactericides, the limestone, the pile cover, or a combination of these factors.

2.2.3 Confidential Mine, Idaho

A silver mine in Idaho conducted a column program to compare and evaluate the effectiveness of bactericides and lime addition to waste rock. The column program was followed by a field trial.

The waste rock used in the columns contained 0.365% pyritic sulphur and 0.119% sulphate sulphur. The net neutralization potential of the material was -14.28 kg CaCO₃ equiv./1000 kg of waste. Three columns were run for 9 weeks: a control (no treatment); a bactericide addition (0.05 g of active ingredient/kg of waste); and a lime addition (14.28 kg/1000 of waste, as per ABA). A summary of the results is presented in Table 2.5.

TABLE 2.5
Summary of Column Tests after 9 Weeks (Parisi *et al.*, 1994)

Parameter	Control	Lime	Bactericide
pH	3.33	3.7	4.3
Acidity, ppm	503	265	78
Sulphates, ppm	708	467	193
Bacteria, log MPN	5	4.3	0
Iron, ppm	32.7	8.9	1.8
Manganese, ppm	2.05	2.49	1.57
Aluminum, ppm	59.9	33.8	1.8
Copper, ppm	2.61	1.96	0.48
Zinc, ppm	5.74	4.14	1.84

The column tests indicated that bactericides would be effective in inhibiting ARD at the mine site. As a result, field trials were initiated. Waste rock was backfilled into previously mined pits. For the field trial, every 18 m lift was sprayed with bactericide at a concentration of 203 kg of active ingredient in 7482 L of water per surface hectare. An untreated control site was also established, and lysimeters were installed in both the treated and untreated areas. Water quality in the lysimeters is being monitored. Over a 15 month period ending in 1993, water in the treated side contained

92.7% less acidity and 70.3% less sulphate compared to the control site. The pH of the treated water was 5.6 (Parisi, *et al.*, 1994). Very limited data were presented.

2.2.4 Equity Silver Mine, Houston, British Columbia

Two independent investigation programs were conducted to assess the effectiveness of bactericides on waste rock produced at Equity Silver. A column program was conducted at the US Bureau of Mines (Watzlaf 1986), and Equity Silver conducted a field study (Patterson, 1987).

Watzlaf (1986) ran 11 columns to evaluate different bactericides at high or low doses on large or small samples. The experimental program is summarized in Table 2.6.

TABLE 2.6
Sample Treatment for Equity Silver Waste (Watzlaf, 1986)

Column #	Sample Wt. (kg)	Treatment	Dosage (mg/kg)	Vol. Water (L)
1	100	Untreated	-	8
2	100	SLS	600	8
3	100	K benzoate	600	8
4	7	Untreated	-	1.2
5	7	Untreated	-	1.2
6	7	SLS	600	1.2
7	7	SLS	60	1.2
8	7	K benzoate	600	1.2
9	7	K benzoate	60	1.2
10	7	K sorbate	600	1.2
11	7	K sorbate	60	1.2

Comparison of the data from the treated and control columns indicated that both potassium benzoate and sodium lauryl sulphate (SLS) were effective in significantly reducing the acidity load and inhibiting bacterial growth (Table 2.7). Low doses of these two bactericides also reduced acidity, but not as much as the higher dose. Potassium sorbate was found to reduce acidity with the high dose only.

TABLE 2.7
Summary of Results (Watzlaf, 1986)

Treatment	Duration of bacterial inhibition ^a (weeks)	Duration of Acidity Reduction ^b (weeks)			Amount of Acidity Reduction		
		100 kg sample	7 kg samples		100 kg sample	7 kg samples	
			High dose	Low dose		High dose	Low dose
SLS	28	29+	29+	8	92%	98%	60%
Benzoate	29+	29+	20	12	84%	>40%	>40%
Sorbate	-	-	20	0	-	>40%	0

^a length of time bacteria were inhibited to less than 1% of the control in the 100 kg samples.

^b length of time leachate acidity was less than 50% of the control.

In an independent study conducted by Equity Silver, the effectiveness of SLS was evaluated in a field trial. Contaminant levels in drainage remained unchanged. SLS was added at a rate based on treating the top metre of the waste rock pile (Patterson, 1987). This dose was approximately 16 times less than the dose used on the 100 kg samples in the other study (Watzlaf, 1986). Furthermore, the depth of oxidation was likely on the order of several metres, so the actual field dosage was much less. It was concluded that the field dosage was insufficient to adequately coat all the rock in the reactive zone, and that, to be effective, the bactericide would need to coat all of the material exposed to oxidation.

2.2.5 Branchton Coal Refuse Disposal Area

The Branchton disposal site, located in Butler County, Pennsylvania, was operated from 1991 to 1993. During this time, the facility was in violation of water quality discharge requirements, particularly manganese. The alkaline addition plan designed for the site failed to neutralize the acidity being generated (Parisi, *et al.*, 1994). A program of bactericide application was implemented as an alternate method to improve the discharge water quality.

The material at the site was refuse from processing coal produced from the Clarion and Brookfield seams. Both seams are known to contain high amounts of contaminants. The coal refuse was sampled and analyzed for sulphur species and neutralization capacity on a monthly basis until August 1992. The material had a total sulphide sulphur content between 11% and 26% and the neutralization potential ranged from 0

kg CaCO₃ equiv./tonne to 737 kg CaCO₃ equiv./tonne. Material with pyritic sulphur content greater than 0.5% was considered to be net acid generating.

The initial remediation plan consisted of placing the material in a pile constructed in an abandoned limestone quarry. The quarry floor (dump foundation) consisted mainly of sandstone. The pile was formed by end dumping material in long rows and bulldozing flat. The permit called for 1.2 metre lifts with 90% to 95% compaction, although compliance varied (J. Horneman, personal communication). A 0.3 metre layer of lime reject with a CaCO₃ equivalence of 40% to 60% and a 0.6 metre layer of locally available alkaline overburden were placed on top of each lift. In addition, caustic soda was applied to the refuse at the cleaning plant on an irregular basis.

The permit specifications were carried out for two layers before it was discontinued. The alkaline overburden was highly clay rich and created semi-permeable layers within the pile. This inhibited the flow of water through the pore spaces, limiting the influx of alkalinity. The alkali application was abandoned when acidic drainage developed.

Bactericides were applied as an alternate method of control. Treatments were applied in December 1991 and January, March and August of 1992. The exact locations of the applications were not recorded, but it is assumed that they were made on different areas of the pile as the deposition of waste continued. Each application, spread on the pile with a hydroseeder prior to overburden placement, included the following ingredients:

- 224 kg of 88% active sodium dodecylbenzine sulfonate per hectare in 3,028 L of water; and,
- 673 kg/ha of controlled-release pellets (16.4% to 27.9% active ingredients).

The effectiveness of the treatments was assessed by monitoring the underdrain water quality, both before and after the bactericide applications. The drainage was sampled monthly and analyzed for acidity, iron and manganese. The underdrain was installed during the construction of the refuse pile.

Water quality prior to treatment was highly variable. Acidity ranged between 250 and 3000 ppm, iron between 100 and 1100 ppm and manganese between 15 and 55 ppm. The levels of these parameters decreased gradually after the first three applications until they averaged 400 ppm, 180 ppm and 6 ppm for acidity, iron and manganese,

respectively (Parisi, *et al.*, 1994). Although these values exceeded the regulatory requirements for the Branchton site, they are significantly less than the pre-treatment water quality results. Water quality data indicate that this reduction is only effective for several months, at which time the levels begin to increase.

Monitoring of the underdrain was discontinued in October 1993 due to plugging of the drain path by sediment in an inaccessible area (J. Plesakov, personal communication). Monitoring continues at the outlet of a small impoundment, located approximately 90 m down gradient of the original sampling location. However, the impoundment collects both underdrain and surface water from the refuse pile. Consequently, it is inappropriate to compare the data sets collected before and after October 1993.

The program cost approximately US\$ 8400 per bactericide application, including personnel training, site visits and testing to determine the effectiveness.

2.3 Discussion

Table 2.8 summarizes the reviewed case histories. Some of the weaknesses common to most of the reviewed case histories include:

- Bactericide effectiveness was assessed primarily by evaluating water quality. The contributions of other measures or factors were not clearly distinguishable.
 - Bactericides can be toxic to aquatic organisms, but none of the reviewed case studies presented monitoring data showing bactericide concentration in drainage.
 - Cost data were seldom collected, or at least not presented.
-

TABLE 2.8
Summary of Bactericide Case Histories

Details	Route 43	Cover Hill	Idaho silver mine	Equity Silver	Branchton
Mine type?	Coal	Coal	Ag	Ag-Au	Coal
Laboratory tests or field trial?	Field	Field	Both	Both	Field
Was control present?	Yes	No	Yes	Yes	No
Was bactericide use tested separately from other methods?	No	No	Yes	Yes	Yes
Water quality data?	Partial	Yes	Yes	Yes	Yes
Bacteria counts reported?	Yes	No	No	No	No
Documented duration?	9 yr.	2 yr.	15 mo.	Not successful	2 yr.
Cost data presented?	No	No	No	No	Yes

The table also indicates that three of the five reviewed studies of bactericide application are related to coal mine wastes. Despite the considerable limitations of these studies, there is enough evidence to say that bactericides can effectively inhibit the onset of ARD in coal wastes.

The effectiveness of bactericide application to metal mine waste is more questionable. Results from the silver mine in Idaho suggest that bactericide application may be effective. However, the better-documented results from Equity Silver Mine suggest that, while some types of bactericide are effective in the laboratory, application of bactericides is not straightforward at field scale.

For both coal and metal mine wastes, the precise mechanisms of bactericide distribution, duration and action, and hence the possible limitations of the method, have not been established. Among the important questions remaining to be resolved are:

- Which bactericides are appropriate for which circumstances, and why?
- What application rates are required for large-scale use?
- What application method (or mixing method) is required to distribute the bactericide effectively?
- What are the site specific conditions that could limit bactericide effectiveness?

The lack of answers to these questions suggest that the use of bactericides as a method to delay the onset of acidic drainage should be considered promising but not proven. In the current state of the art, the use of bactericides needs to be supported by site specific trials, with well-designed experimental controls and with adequate test duration, preferably at both laboratory and field scale.

3.0 PHOSPHATE APPLICATION

3.1 Description

Phosphate combines with iron to form ferrous ($\text{Fe}_3(\text{PO}_4)_2$) and ferric (FePO_4) phosphates in acidic environments. Formation of these compounds can inhibit sulphide oxidation processes in two ways:

- taking ferric iron out of solution thereby limiting further pyrite oxidation; and,
- forming iron phosphate coatings on pyrite grains thereby physically inhibiting access of oxidants to the pyrite.

Phosphate can be added to a waste rock pile in the form of rock phosphate (apatite) during construction of the waste pile, or added to an existing pile using a solution. Rock phosphate is highly insoluble at neutral pH but dissolves in the low pH environment found in porewater in oxidising pyritic materials. In these locations, the phosphate ions complex with Fe^{2+} and form iron phosphate complexes on the surfaces of pyrite grains.

3.2 Case Studies

Many small scale and laboratory studies of phosphate application are presented in the literature. Skousen (1991) and Meek (1991) both found rock phosphate effective in reducing acid generation. In the latter study at the Upshur Complex in West Virginia, apatite with a grain size generally between 0.6 and 1.68 mm was found to be effective in decreasing acidity (Meek, 1991). In a laboratory study, Fyson *et al.* (1995) used natural phosphate rock (6.8% phosphate, 30% calcium) to reduce acidity from metal mine waste with differing amounts of pyrite. Mixing of the phosphate rock with the waste decreased acidity more than layering of the phosphate within the upper portion of the test vessel.

Reduction of pyrite oxidation using solutions of H_2O_2 and KH_2PO_4 has been demonstrated in laboratory studies by Evangelou (1994) and Evangelou and Xing (1992). Pyrite grains were separated from rock and exposed to the solutions. In this technique, the surface of the pyrite is oxidised by the H_2O_2 , releasing ferrous ions. These ions are quickly complexed with phosphate, forming precipitates which coat the grain surfaces.

However, Evangelou has found the combination of H_2O_2 and phosphate was less effective on actual waste rock samples. In humidity column tests containing 40 kg samples of coal mine spoil (20% pyrite) or metal mine waste rock (80% pyrite), the formation of phosphate coatings on pyrite grains seems to vary unpredictably (V.P. Evangelou, personal communication). The reasons for this are unclear and testing is not yet complete.

In the same experiment, better results have been obtained with the addition of calcium (or sodium) hypochlorite ($Ca(ClO)_2$) or bleach (V.P. Evangelou, personal communication). Solid hypochlorite is placed on the top of the sample and is washed through the column by rain water. The hypochlorite ion oxidizes pyrite producing ferric (Fe^{3+}) iron. This reportedly combines with phosphate and/or silica to form a

Only one location was found where phosphate was added to waste rock in the field. This was at a base metal mine in the southwestern United States. Mining of the deposit exposed a section of waste rock significantly higher in acid generating potential than anything previously encountered or found during exploratory drilling. Tri-sodium phosphate was added to the pile which was then covered. The method details and monitoring results for this site are not available for publication.

3.3 Discussion

The currently available information does not demonstrate that phosphate application is a viable technique for delaying the onset of acidic drainage. The most effective form of phosphate (rock or solution) has not been determined, and the need for and function of oxidizing agents is unclear. Results from laboratory studies indicate that the grain size of the waste rock and the phosphate affect treatment efficiency. Presumably these effects would be even more significant at field scale, and would be compounded by the difficulty of mixing the reagents into a heterogeneous waste rock material.

4.0 ALKALI ADDITION

4.1 Description

Alkali addition neutralizes acidity formed by prior or ongoing oxidation within a rock pile. The resulting precipitation of hydroxides and the elevated or neutral pH may also inhibit further oxidation.

Alkali can be added as a solid or as a solution or slurry. It is more efficient to incorporate alkali with the waste rock during pile construction. However, if the waste pile is already constructed, alkali can be added by solution or slurry.

Limestone is a common neutralizing agent, where it is available in sufficient quantities, and where crushing to an appropriate grain size is cost effective. Manufactured neutralizing agents such as lime ($\text{Ca}(\text{OH})_2$), quick lime (CaO), soda ash (Na_2CO_3) and sodium hydroxide (NaOH) are more readily soluble than limestone, and can be cost effective alternatives in some locations. Waste products from other industries, such as lime kiln dust and fly ash, have been used as neutralizing agents.

4.2 Case Histories

4.2.1 Alkali Injection

Alkali injection into waste rock was investigated by Ladwig *et al.* (1985) by pumping hydrated lime slurry into wells at several surface mines in Pennsylvania. Some modest improvements in the discharge water quality were observed. However, overall impact of the alkali injection was minimal.

The inefficiency was attributed to poor mixing of the lime with the waste rock. The lime was in suspension and settled in the absence of turbulence and mixing. This also results in the blockage of pore spaces, leaving the majority of the lime unavailable to porewater flows. Sodium carbonate was also tested and found to be more effective due to its higher solubility. However, benefits were short term, because the soluble alkali was quickly flushed from the system.

4.2.2 Alkali Irrigation

A form of alkali irrigation was investigated by Caruccio and Geidel (1985). Soda ash briquettes and limestone chips were placed in surface trenches that intercepted water before it entered the waste rock. The investigators reported that red coloured seeps became clear with reductions in sulphate, iron and acidity loadings. They concluded that the alkaline water was neutralizing acidity and perhaps also affecting the rate of pyrite oxidation. As a result of the change in pH, the activity of the bacteria was reduced and thus the rate of oxidation was limited.

Two years of monitoring data indicate that trench irrigation is only effective for parts of a waste rock pile (Skousen, 1991). There are several possible reasons. First, the use of trenches to capture water before it enters the waste rock pile was likely to be very ineffective, resulting in only a portion of the water entering the waste being pre-treated. Second, the trenches directed alkaline water to a few select points of entry. Due to channelized flow, only a small portion of the waste rock pile was actually contacted by the water. Third, flow through the trenches was dependent on intermittent precipitation. Consequently, treatment of acid generating areas was also intermittent and the oxidation process may have 'recovered' before the next alkaline flush occurred.

4.2.3 Admixing of Alkali

Admixing of alkali appears to be the most effective way of reducing acidic drainage and is most commonly used in the field. As with phosphate addition, alkali must be thoroughly mixed into a rock pile to ensure that it reaches the oxidation sites. Evans and Rose (1995) attributed acid production from a rock pile, to which sufficient lime kiln dust had been added, in part to incomplete mixing of the alkali with the spoil.

A similar problem was encountered at the Stratmat deposit at the Heath Steele Mine, New Brunswick (MEND Project 2.31.1a, 1990). After laboratory tests showed that layering of limestone in the waste would effectively prevent acidic drainage, a plan to place approximately 15 cm of crushed calcitic limestone on each lift of the waste rock pile was instigated. However, acid was produced from the pile one and a half years after construction. Limestone addition was discontinued and the pile discharge collected and treated. The ineffectiveness of the limestone layers was probably the result of ineffective pore water flow through the layers and possibly the low solubility of the limestone. MEND Report 2.37.1 *Blending and Layering Waste Rock to Delay*,

Mitigate or Prevent Acid Generation – A Case Study Review describes this case study in detail.

4.2.4 Fire Road Mine

The Fire Road Mine is a surface coal mine located near Minto, New Brunswick and operated by New Brunswick Coal Ltd. (NB Coal). Coal was mined at the site from 1983 to 1986. The coal seam was overlain by five to twenty metres of predominantly sandstone with minor conglomerate and shale, and containing disseminated pyrite nodules. One year after operations began, the pH of the mine water was measured at approximately 3 to 4 (NB Coal Ltd., 1995). By the time mining ceased in 1986, approximately 15 million cubic metres of waste rock with an average sulphur content of 0.3% had been disturbed and at least one half to two thirds was above the groundwater table.

A permanent hydrated lime neutralization facility was constructed to treat the mine water. By 1996, the mine had 15 one acre sedimentation ponds containing sludge to a depth of 2.5 to 3 metres. In view of the cost and liability of constructing new ponds, NB Coal reviewed several options for remediating the waste rock, including synthetic and natural capping systems, flooding, alkaline trenches, wetlands, vegetative cover, chemical amendments and relocation of the sludge onto the waste pile. The mine already had approval for perpetual water treatment.

Flooding was impractical because the mine site was located on a topographical high and underlain by fractured bedrock. Relocation of the waste, which had already been exposed to oxidizing conditions, above the water table was determined to be too expensive. Alkaline addition to waste is often ineffective because of difficulties distributing the alkali to the reaction sites in waste rock. Based on cost, long-term maintenance and reliability, relocation of the sludge to the waste piles was viewed as the only viable option for remediation of the waste.

Investigations into the effect of relocating the sludge onto the waste pile on pile hydrology and geochemistry as well as the geotechnical properties of the sludge were undertaken by NB Coal in 1992 and 1994. Short term (one year) geochemical bench tests indicated that sludge amended waste rock maintains a neutral pH, conductivity and sulphate levels an order of magnitude higher than non-amended waste rock and acidity levels an order of magnitude lower (Coleman, *et al*, 1997). Leachates from sludge amended waste rock tests contained significantly lower concentrations of

aluminum, iron and manganese. Calcium concentrations were an order of magnitude higher than the concentrations measured in leachate from non-amended waste rock test cells. Increased sulphate, calcium and conductivity levels would be expected from sludge amended waste rock test cells due to the dissolution of gypsum in the sludge.

Data from the barrel reactors (200 L plastic barrels containing approximately 200 kg of waste rock and 30 kg of sludge placed in the outdoors on site) generally showed the same results as the bench scale weathering cell tests, however, the differences were not as dramatic. The barrel reactors containing amended waste rock had pH levels consistently above the pH measured in the reactors containing only waste rock. pH levels in all barrel reactors remained acidic throughout the year long testing period. Bacterial counts of *T. ferroxidans* were similar in all barrel reactor tests.

In 1992, approximately 50 000 cubic metres of sludge was placed onto the recontoured waste rock pile. The effect of sludge placement was a short term increase in pH and decrease in acidity. Since the initial field trial, four to six sludge ponds are dredged annually and their contents placed on the waste rock. The ponds are then reused, eliminating the cost of pond construction.

Table 4.1 summarizes water quality monitoring data from the site (M. Coleman, personal communication; NB Coal Ltd., 1995). Despite wide variability in the data, it is clear that sulphate, acidity, aluminum and iron concentrations have decreased.

TABLE 4.1
Fire Island Road Water Quality Data

Monitoring Period	Acidity (mg CaCO₃ equiv. /L)	Fe (mg/L)	Al (mg/L)
Typical values in 1990	2000	60	160
Average of daily samples 1993-1995	813	37	116

Acidity, total iron and total aluminum have decreased by approximately one half and values are even lower for several months following dredging (M. Coleman, personal communication). In addition, lime consumption by the neutralization plant has decreased significantly. However, it is unclear how much of the decrease in metals concentration is the result of natural depletion of pyrite in the exposed waste rock and how much can be attributed to the sludge.

4.2.5 Absetzerhalde Relocation, Germany

Uranium mining was carried out in the Ronneburg District from 1950 to 1991. Mine workings within the district include the Lichtenberg pit, an extensive network of underground workings and fourteen waste rock piles, all within an area of about 800 hectares. As part of the remediation plan, many of the waste rock piles will be moved into the open pit. Quicklime (CaO) is added to neutralize stored acidity in waste rock that will ultimately be below the water table. The relocation and lime addition programs are described in detail in a number of German language reports. Two recent articles in English provide a good summary and list the German references (Chapman, *et al*, 1998, Hockley, *et al*, 1997).

The lime addition program is based on extensive field and laboratory tests. Quicklime was selected as the alkali source to minimize the generation of excess carbon dioxide, which it was thought would enhance uranium solubility. Quicklime addition to acidic rock was tested in laboratory column studies, and showed that the quicklime would be 80% reactive.

The quicklime is added during the excavation of the waste rock from the piles, and prior to backfilling in the pit. The waste rock is excavated in a series of 10 m high benches. The lime is spread along the crest of each working face, and then pushed down the face by a D-11 dozer. The rolling action in front of the dozer provides mixing. The pushed material is then loaded into haul trucks and transported to deposition sites in the Lichtenberg Pit, where it is dumped and spread in 1-m lifts, providing further mixing.

Results of the column studies were correlated with paste pH and conductivity to derive a set of rules by which the lime addition rate could be varied as rock with different acidities was encountered. The lime addition control program was tested at field scale to determine appropriate sampling and testing frequencies. The final control program used drillholes and ABA tests for long term planning, but varied the short term lime addition rate on the basis of test pits excavated at 25 m centers in each 10 m lift.

4.2.6 Flambeau Mine, Wisconsin

The Flambeau Mine was permitted in 1991 and ceased operations in 1997. Copper, gold and silver ores were mined. Backfilling of waste rock into the pit was identified during permitting as a key component of the closure plan. During operations, waste rock was sorted and placed in two stockpiles. Waste rock with a sulphur content less than 2% was placed in the “Type I” stockpile, while waste rock with greater than 2% sulphur was placed in the “Type II” stockpile. It was recognized at the time of permitting that alkali would need to be added to the Type II waste rock to neutralize acidity that would accumulate during the time that the rock was on surface. The alkali addition program is described in Chapman *et al* (1998) and references therein.

A two phase program of field and laboratory testing of alkali additions to the waste rock was initiated in 1996. Test pit samples were taken from both the Type I and Type II stockpiles and tested on site using a field “alkali demand test”. The test involved addition of increments of milk of lime to subsamples of the waste rock, and 24-hour equilibration. The lowest milk of lime addition resulting in neutral pH after 24 hours was used to estimate the acidity stored in the sample. The field test was calibrated against titrations.

Saturated column tests were carried out to select the most appropriate alkali source and to determine appropriate availabilities. Limestone was selected as the most appropriate alkali source because it buffered pH in the neutral pH range even if it was added in excess, and because it would not be washed out by reflooding groundwater. The limestone NP was determined to be 70% available for acid neutralization reactions.

During the relocation, alkali addition rates were controlled by test pit samples on a regular grid (60 feet on flat surfaces and 30 feet on side slopes). Samples were classified into four groups on the basis of paste pH and conductivity. Limestone addition rates were conservatively set to be at the high end of alkali demand for each group. Areas of similar alkali demand were delineated ahead of the relocation, and limestone was distributed over the surface using scrapers. The waste rock was then loaded into haul trucks by one of two methods, a backhoe reaching downwards from the crest of the excavation face, or a loader working at the bottom of the face. In the case of the latter method, the loader would undercut the slope to promote mixing of the limestone. In the pit, the waste rock and limestone were dumped and spread in three-foot thick lifts to further promote blending.

Quality control samples taken from the backfilled pit clearly showed that the acidity of the waste rock was neutralized. Although the initial pH of the waste rock ranged from 1.6 to 8, the backfilled material had a pH between 5.7 and 7.8. The paste conductivity range was shifted from 0.1 - 6.4 mS to 0.1 - 2.4 mS.

4.3 Discussion

Table 4.2 summarizes the reviewed case studies. It is clear from the reviewed case studies that direct addition of alkali can neutralize the acidity contained in waste rock that has already undergone oxidation and acid generation. The most important limitation on the effectiveness of alkali addition for this purpose appears to be the degree of mixing of the alkali with the acidic material. Direct blending, such as is possible during relocation of waste, has been shown to be effective. The application of solutions, slurries or sludges to a pile surface, and the layering of alkali within a pile, are apparently less effective.

Presumably, if the alkali addition is able to neutralize existing acidity and maintain neutral pH, it will inhibit the more rapid oxidation processes that would occur in a lower pH environment. In that sense, the alkali addition can be said to delay further acid generation. There may be additional benefits in this respect, caused by the coating of sulphide surfaces by hydroxide precipitates. However, none of the reviewed cases attempted to use alkali addition as a method of delaying acid generation, and therefore no data on these effects were collected.

The application of alkali to a neutral pile, in an attempt to delay the onset of acidic drainage, was not tested in the case histories reviewed herein. The recent review of waste rock blending and layering (MEND Report 2.37.1) has more information on such cases.

TABLE 4.2
Summary of Alkali Addition Case Histories

Details	Injection & Irrigation	Heath Steele	Fire Island Road	Absetzer-halde	Flambeau
Mine type?	Coal	Pb-Zn-Au-Ag	Coal	Uranium (black shale)	Cu-Zn
Alkali type?	Various	Limestone	Neutralization sludge	CaO	Limestone
Application method?	Surface injection & irrigation	Layering	Surface deposition	Blending during relocation	Blending during relocation
Laboratory tests or field scale?	Field	Both	Both	Both	Both
Was control present?	?	Yes	Yes	Yes	Yes
Was alkali addition tested separately from other methods?	Yes	Yes	Yes	Yes	Yes
Water quality data?	Yes	Yes	Yes	Yes	Yes
Acidity neutralized?	Variable	No	Partial	Yes	Yes
Cost data presented?	No	No	No	No	No

5.0 LOW PERMEABILITY COVERS

5.1 Description

Low permeability covers are designed to reduce the amount of water infiltrating the pile, thereby reducing the mobilization of oxidation products already present in the material. Covers can also be engineered to limit the amount of oxygen that enters the pile, thereby inhibiting sulphide oxidation.

Both synthetic HDPE covers (SRK, 1991) and soil covers (Equity Silver Mines Ltd., 1995; Yanful and St. Arnaud, 1991; Yanful, 1991; Ritchie and Harries, 1987) have been used to control acid generation in waste rock. Because of their relatively high cost, synthetic liners are unlikely to be used as a method to delay acid generation.

Simple soil covers consist of only one layer. Composite soil covers consist of layers with different functions. Typical layers and functions include:

- A surface vegetation layer, to enhance evapotranspiration and reduce erosion;
- A thick layer of uncompacted, silty soil, to provide water storage and reduce the head on underlying layers;
- A low permeability layer of compacted silty or clayey soil; and
- A “bedding layer” between the cover and the rock.

5.2 Case Histories

5.2.1 Bersbo Mine, Sweden

The Bersbo Mine in Sweden produced copper from the 1300s to the early years of this century. Ore was hand sorted during the days of operation, consequently, only waste rock piles were left. Experimental work on concentrating zinc that was carried out in the 1930s resulted in a small tailings pond on the site.

The ore contained chalcopyrite, galena, pyrite and pyrrhotite. The average metal content of the mined ore was probably 0.5-3% copper, 1-3% zinc, 1% lead, 20% iron and 25% sulphur. It is likely that the waste rock also contained these minerals. The waste rock was initially disposed in several small piles covering 19,000 ha. These were

backfilled into the shafts and the remaining material consolidated into two piles in 1987, reducing the aerial extent to 9,000 ha.

The bulk of the waste rock has been exposed for 100 to 150 years. Surface and ground water were probably polluted by the end of the 1800s. Drainage from the mine site flowed into a nearby lake with pH below 4, 50 - 150 mg/L zinc, 5 - 15 mg/L copper and 0.2 - 0.6 mg/L cadmium.

The two remaining waste rock piles were first covered with tailings as a filter layer to prevent the transport of fines from the sealing layer into the waste rock. Two different sealing layers were used, one on each pile. One pile was sealed with crushed rock grouted with Cefyll, which is a cemented fly ash mixture capable of being pumped into place and then hardening. The other pile was sealed with compacted clay. Both piles were then covered with approximately 2 m of glacial till to provide protection to the sealing layers. Finally, the covers were vegetated with pine and birch plants.

Monitoring of the site has included the water quality in the surface and groundwater around the waste rock piles and in the neighbouring lake, and the infiltration of water and oxygen through the sealing layers. Discharge from the underground workings was mixed with the discharge from the Cefyll covered pile. Consequently, the impacts of the covering cannot be accurately assessed and as such, the data is not presented in this report. Water quality monitoring was started in 1987 at the other pile, two years before the clay cover was installed. The mean, minimum and maximum values of the pre- and post-cover time periods for the clay covered pile are presented in Table 5.1.

TABLE 5.1
Water Quality of Discharge From The Clay-Covered Waste Rock Pile at Bersbo,
Sweden (Lundgren And Sanden, Personal Communication)

Parameter		Before Cover avg. 1987-1989	After Cover avg 1993-1996
pH (s.u)	minimum	2.88	4.71
	mean	3.42	4.86
	maximum	4.14	4.98
SO ₄ (mg/L)	minimum	139	376
	mean	737	1019
	maximum	2047	1367
Cu (mg/L)	minimum	0.45	0.033
	mean	8.4	0.046
	maximum	22.9	0.084
Fe (mg/L)	minimum	0.26	46.
	mean	8.8	423.
	maximum	76.9	525
Zn (mg/L)	minimum	0.37	11.2
	mean	70.6	16.8
	maximum	189	22.9

Infiltration monitoring showed that the covers were effectively minimizing the amount of water and oxygen entering the piles. The hydraulic conductivity of the two covers were less than 10^{-9} m/s. The water infiltration rate in the clay covered pile was 0.5 to 3 mm per year. No water infiltration was detected in the Cefyll covered pile one year after cover installation. Oxygen concentration in both piles, one year after the covers were placed, were less than 1%, down from 20% measured prior to the cover installation (Lundgren, 1990).

The water quality data collected to 1996 indicate a reduction in the variability of parameter concentration. Overall, pH has increased and copper and zinc concentrations have significantly decreased. On the other hand, iron concentrations have significantly increased along with a moderate increase in sulphate over the same time period. The researchers did not confirm a mechanism explaining the observations. However, one hypothesis is the anoxic environment within the waste rock pile limited the amount of Fe²⁺ oxidized to Fe³⁺. Consequently, Fe²⁺ remains in solution, giving a higher iron concentration in leachate discharge at the toe of the dump. It would be expected that the iron would oxidize and precipitate downstream from the dump after being exposed to the atmosphere.

5.2.2 Equity Silver Mine, British Columbia

The Equity Silver Mine was an open pit copper, silver and gold mine in central British Columbia, operating from 1980 to 1994. The ore was extracted from three pits, producing approximately 85 million tonnes of waste rock. The dominant sulphides in the waste rock were pyrite, tetrahedrite and chalcopyrite. Of the total waste rock tonnage, approximately 8 million tonnes were determined to be net acid consumers and were used in road and tailings dam construction. The remaining waste rock went into three waste rock piles – Main, Southern Tail and Bessemer. Approximately one third of the Southern Tail pile was backfilled into the Southern Tail pit under a water cover. The remaining material is above the water table. Waste rock that was not flooded has been covered with one metre of till.

Acid base accounting (ABA) was conducted in the late 1970s prior to mine development. These tests indicated that the wastes would not generate acidic drainage. In 1981, one year after mining began, acidic drainage was detected from the waste rock piles. Later in the mine life, approximately 160 samples were collected from the upper benches of the Main pit and submitted for ABA testing (Morin, 1991). The range in neutralization potential was 0.27 to 184.1 kg CaCO₃ equiv./tonne (median 13.43) and the acid potential ranged from 3.75 to 226.9 kg CaCO₃ equiv./tonne (median 45). Although rock type was not recorded for each sample, the gabbro, andesite and latite dikes were not acid generating. Gabbro and latite was segregated during mining and used for dam and road construction.

Each of the three waste rock piles were constructed on natural till. Instability in one section of the pad forced the angle of the pile slopes to be decreased to 20 degrees from the natural angle of repose (Patterson, 1987). The characteristics of each pile are summarized in Table 5.2.

TABLE 5.2
Dates of Construction and Quantities of Material as of December 31, 1994

Pile	Construction Date	Acid Generating Waste (mt)	Potentially Acid Generating Waste (mt)	Non-Acid Generating Waste (mt)	Area (ha)	Cover Completion Date
Main	1980 - 1993	43.1			48	1994
Southern	1985 - 1986	12.0	5.0	0.5	41	1991
Tail Bessemer	1986 - 1994	15.9			29	1994
TOTAL		71.0	5.0	0.5	118	

Soil covers and synthetic membranes were considered during planning for closure (Mike Aziz, personal communication). It was determined that a soil cover was best due to a nearby source of suitable till and that covering large areas of waste rock with membranes was too impractical and costly.

Each of the piles was recontoured and covered with a layer of compacted glacial till approximately 0.5 m thick overlain by a layer of loose till approximately 0.3 m thick. The compacted till was designed to remain at least 85% saturated at all times to minimize precipitation infiltration and oxygen ingress to the pile. The uncompacted till acted as an evaporation buffer between the air and the lower till layer as well as containing seasonal fluctuations in water content (O’Kane, 1996).

In 1993, a five year study was begun to collect data to determine the effectiveness of the till cover to reduce water and oxygen infiltration (O’Kane, *et al.*, 1995). The piles were instrumented to monitor oxygen concentration and water percolation. The field program is summarized in Table 5.3.

TABLE 5.3
Summary of Field Instrumentation Installed in the Waste Rock Dumps and Soil Covers at Equity Silver Mines (O’kane, *et al.*, 1995)

Instrumentation	Number	Comments
lysimeters	14	at base of cover
O ₂ /CO ₂ probes	7 (locations)	in waste rock
temperature probes	7 (locations)	in waste rock
weirs	4	surface runoff from dump area
weather station	1	
thermal conductivity sensors	24 (3 locations of 8 each)	matric suction and temperature
neutron probe access tubes	14	water content
local runoff reservoirs	2	next to main instrument sites
jet-fill tensiometers	12 (2 nests of 6 each)	installed during site visits

Initial results indicate that the compacted till layer has maintained 85% saturation over a two year period (O’Kane, *et al.*, 1995). Water quality of the waste rock drainage has been monitored since shortly after the piles were constructed. Water flows from the Main and Southern Tail piles were measured directly while data for the Bessemer pile was calculated from other flows.

Flows from the Main and Bessemer piles, the Southern Tail pit, plantsite, Getty Creek pond and various sumps were collected in the Main Pond (Equity Silver Mines Ltd., 1996). Water from the other ARD source, the #1 Dam Seepage, was collected in the Storage Pond. The Main Pond water quality is used to track acidic drainage and metal concentration trends. Samples from the Main Pond were collected on a regular basis and analyzed for immediates (pH, acidity and sulphate) and selected metals at Equity’s on-site laboratory and Placer Dome Canada’s laboratory in Vancouver. The average annual value for each parameter is presented in Table 5.4.

TABLE 5.4
Average Annual Parameter Concentration in the Main Pond Before and
after Cover Installation (1994)

Parameter	1991	1992	1993	1994	1995	1996
pH	2.6	2.59	2.67	2.52	2.42	2.4
acidity (mg/L)	12556	10550	10647	9101	8076	8930
SO ₄ (mg/L)	17822	13364	16153	22340		
Cu (d) (mg/L)	191	133	145	116	93	102
Fe (d) (mg/L)	2097	1415	1407	1650	1243	1452
Zn (d) (mg/L)	203	194	224	194	151	122
Flow (m ³ /s)	0.0256	0.0264	0.0295	0.0302	0.0231	0.0354

The data shows that acidity and zinc loadings have decreased after the cover installation. The remaining parameters display variability with flow rate from the Main Pond. As there are many sources to the Main Pond in addition to the covered waste rock piles, the impact of the soil cover on water quality cannot be precisely determined. Furthermore, the waste was allowed to oxidize for many years prior to being covered, so that any changes to oxidation rates will only be noticeable over the long term.

The average cost for reclamation was estimated at \$35,000/ha (Mike Aziz, personal communication). This included resloping, excavation, transportation and placement of the compacted and uncompacted till layers. Reseeding cost an additional \$400/ha (Mike Aziz, personal communication). Annual water monitoring costs were estimated at \$60,000 to \$70,000.

5.2.3 Heath Steele Pile 7/12

As part of MEND Project 2.31.1 Heath Steele Waste Rock Study, a small waste rock pile (7/12) at the Heath Steele mine was relocated to a prepared test pad in June of 1989. In September 1991, the pile was covered with an extensive composite cover consisting of soil, sand and gravel layers.

The waste rock comprising Pile 7/12 was generated from a massive lead-zinc-gold-silver sulphide deposit hosted in volcanic tuffs and sediments. The rock was mined in the early 1960s and had been on the surface since that time (Alan Bell, personal communication). Grab samples from the waste rock were submitted to the Research and Productivity Council in Fredericton, New Brunswick for sulphide mineralogy. The results indicated that the waste rock contained 7 - 10% pyrite, 5 - 7% FeS, less than

1% of pyrrhotite and less than 1% of other sulphides, such as galena, sphalerite, chalcopyrite, etc. Acid base accounting was also conducted on the grab samples, using the BC Research methodology. The two samples had a net neutralization potential of -204.6 and -216.0 kg CaCO₃ equiv./tonne of waste rock. The neutralization potential to acidity production ratio was 0 for both samples.

Pile 7/12 was constructed on a 50 m x 50 m prepared pad of compacted sand that was free of protrusions (Nolan, Davis and Associates, 1990). An impermeable membrane made of Fabrene fabric strips was placed over the sand base. The strips were glued together to create three large panes and folded over for two feet in several places to accommodate any expansion or movement.

The membrane was then overlain by a 150 mm layer of medium to coarse sand composed of 4% gravel, 90% sand and 6% silt-clay. This material was compacted with at least 4 passes of a 5 tonne vibratory compactor.

An underflow drainage collection system consisting of 50 mm diameter schedule 80 PVC drain pipe was installed within the upper sand filter layer. The outlet of this system was installed with a U-bend water trap to prevent air from being drawn into the base of the waste rock pile.

The pile was constructed using approximately 14,700 tonnes (6 200 m³) of pyritic waste rock. Material was end dumped along the perimeter and then pushed into the middle of the membrane with a front end loader. Vertical pipes of 150 mm diameter were set into the rock till. After construction, these were removed to create vertical holes into which instrumentation was placed. A perimeter ditch was constructed for collection of surface runoff.

The pile was contoured into a dome with a maximum depth of 5 m and a maximum slope of 3:1 (H:V). The surface area of the pile was approximately 2 100 m². Prior to placement of the till cover, the pile was contoured and low sections filled in with excavated waste rock and non-acid generating crushed rock (Yanful *et al.*, 1993a). A total of 50 tonnes of crushed rock was used to prepare the surface. Material was removed by hand from the base of the pile to expose the membrane. An additional membrane was attached to the edge of the liner and integrated into the till cover to ensure that the pile remained a closed hydraulic system, with all precipitation reporting

either to the underdrains or the perimeter drains. Details of the cover construction are presented in Yanful *et al.*(1993a).

Instruments to measure pore gas and temperature were mounted on piezometers at six locations on the top and sides of the pile. The piezometers were made of 38 mm internal diameter PVC tubing. Two lysimeters, having an area of approximately 6 m², were installed in the pile below the cover. Details of the instrumentation can be found in Nolan, Davis and Associates (1990). The underdrains channel the water to an outlet on the north side of the pile. Water quality has been monitored in the runoff and from the underdrains since the pile was relocated in June of 1989. Temperature, oxygen and water quality data are presented in Tables 5.5, 5.6 and 5.7, respectively.

Results indicate that both temperature and oxygen decreased immediately after cover placement. Oxygen in the pile decreased from a range of 8.2% to 14.5% to a range of 0.2% to 0.7% in 1993 (Bell *et al.*, 1995). The decrease in temperature was less significant, although the cover reduced temperature fluctuations.

Infiltration into the pile has been calculated for a two year period. Measurements of the volume of water in the lysimeters indicate that approximately 2% of the precipitation infiltrated the pile at the lysimeter locations (Bell *et al.*, 1995). Infiltration into the pile as a whole was even less, approximately 0.08% over the two year period.

Water quality data show that acidity, sulphate and metal concentrations fluctuate widely between seasons. Overall, acidity and sulphate remained at the same concentration after the cover installation with the range decreasing for acidity and increasing for sulphate. Minimum sulphate values after cover installation were lower than before, suggesting that water quality may have improved during certain parts of the year. pH values increased slightly after cover installation, further suggesting that some water quality improvement had been accrued from the soil cover.

Of particular interest is iron. The concentration of dissolved iron clearly increased after the soil cover was placed on the pile. This trend was also observed in the Bersbo tests (Section 5.2.1). The oxygen concentrations measured in Pile 7/12 after covering were less than 1%. These concentration may be sufficiently low to inhibit conversion of the more soluble Fe²⁺ to the less soluble Fe³⁺.

The waste rock used in Pile 7/12 had been exposed to the atmosphere since the 1960s. Although the cover has likely minimized any new sulphide oxidation, a significant amount of oxidation products would have been produced and stored within the pile during the 30 years of exposure. As water continues to percolate through the pile, these oxidation products will dissolve and become mobile. Therefore, significant improvements in water quality will likely be observed only after these products have been flushed from the pile.

TABLE 5.6
O₂ Concentration Data

Sta	Depth (m)	Min.	Max.	Avg.	1988	1989					1990					1991	1992		1993	
					Jul-04	Aug-03	Sep-04	Sep-22	Oct-13	Nov-22	Apr-25	May-25	Jun-14	Jul-20	Aug-16	Sep-28	Oct-12	September	January	July
1	1.4	15.2	20.8	19.3	18.4	19.0	20.4	20.3	20.8	19.9	20.8	20.5	15.2	17.7	19.5	19.5	18.0			
	0.5	14.3	20.8	18.9	17.8	19.0	20.1	20.3	20.8	19.0	19.6	20.5	14.3	17.5	19.0	19.5	18.0			
	0.4	14.5	20.8	19.1	18.0	18.5	20.4	19.8	20.8	20.0	20.6	20.5	14.5	17.5	18.5	19.2	17.5			
2	3.9	0.5	17.9	11.8	0.5	0.5	16.6	17.6	14.1		17.9	15.0	12.7	11.0	17.2	13.5	11.5			
	2.4	5.0	17.5	12.1	5.0	5.4	12.5	14.8	14.5	15.3	17.5	15.2	11.6	9.1	14.0	10.5	10.5			
	1.9	5.0	15.9	10.8	5.0	5.2	10.3	13.3	13.0		15.9	14.0	11.3	9.0	12.6	11.5	9.2			
	1.4	4.7	16.8	11.0	5.0	4.7	12.0	12.5	12.5	11.0	16.2	16.8	10.0	9.5	13.5	10.5	9.3			
	0.9	3.9	20.5	11.8	6.3	3.9	10.5	11.0	13.5		16.6	20.5	8.5	15.5	13.5	15.5	9.3			
	0.4	3.2	20.9	13.6	5.8	3.2	12.5	10.7	18.7	15.8	15.5	20.9	13.0	19.8	19.5	19.0	8.5			
3	4.1	6.0	18.8	14.6	6.0	6.4	14.8	16.5	18.0	17.0	18.8	18.0	14.0	16.7	16.4	15.0	13.5	max.=13.5	max.=9.7	max.=0.8
	2.9	7.1	20.4	14.7	7.3	7.1	14.0	16.0	17.5		20.4	20.0	14.2	16.0	16.6	14.0	13.0	min.=7.5	min.=4	min.=0.5
	2.4	7.2	18.9	14.2	7.3	7.2	13.5	14.8	17.7	15.0	18.9	18.0	13.5	15.6	16.0	14.5	13.0			
	1.9	6.5	16.6	11.6	7.0	6.5	11.5	12.3	16.0		16.6	13.5	10.5	10.4	10.3	10.0	8.4			
	1.4	7.5	17.0	13.1	7.8	7.5	13.2	13.3	16.2	15.5	17.0	15.0	11.3	13.8	12.2	12.5	11.0			
	0.9	7.1	17.9	13.3	7.5	7.1	13.4	14.2	15.2		17.9	17.5	11.7	14.8	14.2	15.0	12.0			
	0.4	0.0	20.8	13.0	7.0	6.6	14.5		15.2	14.8	18.0	20.8		19.8						
4	4.3	8.6	19.5	15.8	9.0	8.6	15.5	17.5	19.0	17.8	19.5	18.0	15.5	17.5	20.5	16.2	15.5			
	2.8	10.5	19.5	16.7	11.0	10.5	17.8	19.5	19.5		19.5	18.0	16.1	18.4	16.2	18.5	16.5			
	2.3	10.5	19.9	16.9	11.0	10.5	17.6	19.3	19.8	19.0	19.9	17.5	16.0	18.5	16.4	18.2	16.2			
	1.8	10.2	19.6	16.5	11.2	10.2	17.6	19.3	19.6		19.4	17.1	15.6	18.5	16.0	18.0	16.5			
	1.3	10.0	19.5	16.6	10.5	10.0	17.5	18.9	19.5	19.5	19.4	17.2	15.4	18.2	15.5	17.5	16.0			
	0.8	10.0	19.4	16.0	10.5	10.0	17.0	17.6	19.4		19.1	17.2	15.0	18.2	15.5	17.5	15.2			
	0.3	9.8	19.5	16.4	10.0	9.8	17.0	17.5	19.5	19.0	19.1	18.0	16.0	18.2	15.7	17.5	15.5			
5	3.7	16.6	20.8	19.5	19.5	19.5	20.8	20.5	20.0	20.0	20.5	17.7	16.6	19.5	13.6	19.5	18.5			
	2.3	12.5	20.8	19.1	20.0	20.0	20.8	20.5	20.7		20.5	12.5	17.0	20.2	16.6	20.0	20.0			
	1.7	17.0	20.8	19.8	20.5	20.0	20.8	20.4	20.0	19.5	20.5	19.0	17.0	20.0	16.7	18.0	17.5			
	1.2	16.8	20.7	19.5	20.0	20.0	20.7	20.3	20.7		20.5	16.8	16.9	19.8	15.9	18.2	17.7			
	0.7	16.5	20.8	19.6	20.8	20.0	20.5	20.2	20.5	20.5	20.5	16.5	16.8	19.8	15.9	18.5	17.5			
	0.2	16.2	20.8	19.1	20.8	19.0	20.8	18.8	20.1	19.5	20.4	16.5	16.2	19.1	15.5	18.0	17.5			
6	2.1	18.0	20.8	20.5	20.8	20.8	20.8	20.8	20.8	20.8	20.8	18.0	20.8	20.5	20.6	20.5	20.5			
	0.6	17.3	20.8	20.2	20.8	20.5	20.5	20.3	20.7	20.8	20.5	17.3	20.4	20.5	20.4	20.2	20.2			
	0.1	19.7	20.8	20.4	20.8	20.5	20.5	20.0	20.7	20.8	20.4	20.8	20.0	20.8	19.7	20.2	20.0			

TABLE 5.7
Water Quality Data

Date	pH	Acidity (mg/L)	Sulphate (mg/L)	Lead (mg/L)	Iron (mg/L)	Copper (mg/L)	Zinc (mg/L)	Aluminum (mg/L)	Total Solids (mg/L)
SURFACE RUNOFF									
July 1989	2.8	22000	22970	0.029	1700	320	8000		
August 1989	2.0	45500	54285	0.002	9810	430	13350		
September 1989	3.0	40100	47500		6590	420	11000		79300
April 1990	2.4	48500	70500		10600				
May 1990	2.4	44700	40000		16900				
August 1990	2.1	62000			18800		6930	2160	118000
September 1990	2.2	67850	55165		11924				
October 1990	2.2	56500			3600			246	101000
Overall Average	2.4	48394	48403	0.0155	9991	390	9820	1203	99433
UNDERDRAINS									
July 1989	2.4	44000	43440	0.186	5100	970	12700		
August 1989	2.2	15800	21328	0.002	3550	615	7895		
September 1989	2.8	30500	28000		2800	910	8000		53100
April 1990	2.5	16400	17000		3510				
May 1990	2.4	16400	12700		5510				
August 1990	2.1	44800			13767				81300
September 1990	2.2	73250	32970		7920		9730	3150	
October 1990	2.1	64400			3700		8700	2820	11200
Overall Average	2.3	38194	25906	0.094	5732	832	9405	2985	48533
Range in 1992	2.3-2.9	1800-54450	5140-71042		15800-54000				
Range in 1993	3.0-3.2	na	9970-73854		5000-30844				

5.3 Discussion

The reviewed case studies all applied low permeability covers as long-term ARD control methods, rather than as temporary delays. Also in all cases, the primary objective of the cover was to reduce infiltration and thereby to limit the mobilization of existing oxidation products. Given the extensive oxidation of the waste rock prior to construction of the covers, any effects on current and future acid generation are unlikely to be noticeable in the short term. Nevertheless it is clear that a well-designed and constructed soil cover can reduce the amount of oxygen in the waste rock, and would therefore be effective in delaying the onset of acid generation.

The question of what constitutes a “well designed and constructed” soil cover is site and case specific. If the design objective is only to limit oxidation and delay the onset of acid generation for a period of a few months, a simple cover may be adequate. To limit oxidation over longer periods, the cover design would include at least one layer that remains at or near water saturation (saturated soil is virtually impervious to oxygen). In all cases, the design needs to take into account the local climate and the local availability of soil materials. For example, the fine-grained material needed to form low permeable layers is often difficult to find.

Assuming that site specific considerations are properly accounted for, soil covers can be considered proven technology for delaying the onset of acidic drainage.

The soil cover case histories described above are notable for another reason. They are generally very good examples of how field-scale demonstrations of any of the “delay” methods should be carried out. The Heath Steele study, in particular, has benefited from a very careful design that included consideration of experimental controls, material characterization, monitoring of all inputs and outputs, and attempts to measure conditions within the test piles.

6.0 FREEZING

6.1 Description

In Canada and other countries, many mines are located in mountainous areas with extreme winter conditions or in areas of permafrost. Freezing and low temperature storage may be effective as a delay technique for short-term storage by slowing the sulphide oxidation rate such that the available alkaline material can neutralize the drainage prior to exiting the waste rock pile.

6.2 Case Studies

Two studies have been carried out to investigate the behaviour of tailings in very low temperature conditions. Although a number of mines have proposed “freeze-back” of waste rock as a long term closure measure, no case histories involving waste rock were found,

The first tailings study was conducted by CANMET on material from Homestake's Cullaton Mine. The study consisted of two phases. The first phase assessed the acidic drainage potential of tailings at 25°C. The second phase involved a column leach study of tailings (from the same area as the samples used in Phase I) conducted at 2°C for 24 months followed by 12 months at 10°C and monitoring the water quality. Results indicate that the cold temperatures were effective in slowing sulphide oxidation rates. However, acidic drainage was produced near the end of the two year period at 2°C when the alkalinity in the sample had been consumed. An estimated 11% of total sulphur was mobilized from the oxidation of sulphides during the first two years of the Phase II study. The oxidation rate increased when the samples were warmed up to 10°C, but remained lower than the rates observed at 25°C. It is concluded that low temperature storage can slow down the rate of oxidation. The amount of delay before acidic drainage is generated depends on the amount of alkaline material present in the tailings. All samples produced acidic drainage at 2°C (Davé, 1996).

The second study, which was sponsored by the Department of Indian and Northern Affairs (DIAND), came to a similar conclusion in regard to acid generating tailings at two Canadian mine sites in regions of permafrost (Dawson and Morin, 1996). The report also outlined the acid generation processes related to cold temperatures and suggested areas of further research.

6.3 Discussion

Although results from the tailings studies suggest that permafrost can delay the onset of acidic drainage in tailings, the findings are far from conclusive, and cannot be readily extrapolated to waste rock. The much coarser grain size of waste rock means that it will not retain water as well as tailings, and therefore will have much different thermal behaviour. Furthermore, the potentially rapid air transport through waste rock means that oxidizing conditions can be initiated more rapidly and to a greater depth than in tailings. The heat produced by sulphide oxidation will then make it difficult to freeze waste rock.

The use of freezing as a method to delay the onset of acidic drainage in waste rock remains promising but unproven.

7.0 INORGANIC OXYGEN-CONSUMING LAYER

7.1 Description

An inorganic oxygen-consuming cover layer consists of rock that has a sufficient sulphide content to consume infiltrating oxygen, but a favourable NP:AP ratio so that net acidic conditions do not develop. The layer is intended to cover waste rock with a less favourable NP:AP ratio and consume oxygen before it reaches the potentially acid generating material.

The concept has not been attempted at the field scale. It has, however, been incorporated into conceptual reclamation planning for the Ronneburg uranium mining district in the former East Germany.

7.2 Case History - Nordhalde, Germany

Uranium mining was carried out in the Ronneburg District from 1950 to 1991. Mine workings within the district include the Lichtenberg pit, an extensive network of underground workings and fourteen waste rock piles, all within an area of about 800 hectares. As part of the remediation plan, many of the waste rock piles will be moved into the open pit. Waste rock with the lowest NP:AP ratios is being placed below the ultimate water table. Due to volume constraints, some potentially acid-generating material will remain above the water table. The current plan is to minimize oxygen access to the potentially acid generating rock by constructing a low permeability spoil cover over the backfilled pit. Waste rock that contains some sulphides, but has an NP:AP ratio of greater than 3, will be placed directly beneath the cover. This so-called C-Zone is intended to consume any oxygen that penetrates the cover. (Gatzweiler *et al.*, 1997)

Recent investigations at the site have focused on a waste rock pile called the Nordhalde, which contains potentially acid generating material overlain by a layer of high NP:AP material, and covered with a rudimentary soil cover. One objective of the investigations was to determine whether the overlying Class C material functions effectively as an inorganic oxygen-consuming layer.

The Nordhalde was constructed on the west side of the Lichtenberg open pit. The dump is approximately 84 hectares in plan area, containing about 27 million cubic metres of material. The overall composition of the waste rock pile is approximately 40% Devonian limestones and slates, 30% ochre limestone, 20% Silurian siliceous and alum slates, 5% Ordovician leather slates and 5% diabase. The pile has an average pyrite content of 3.6%, although composition within the pile can vary widely with localized pockets containing up to 17% pyrite.

The waste rock pile was characterized by a program of drilling, sample collection, and static and kinetic testing. The acid production (AP) and neutralization potential (NP) values from the drillhole data were compared to the following criteria to classify the material:

NP:AP < 1 - indicates a net acid generation potential (Class A);

1 < NP:AP < 3 - indicates an uncertain potential for net acid generation (Class B); and

NP:AP > 3 - indicates a net acid consumer (Class C).

The NP:AP data were plotted on sections and interpreted using ordinary kriging and polygonal interpretation. From these methods, volumes of each class of material were estimated:

Class A = 15.47 million m³

Class B = 8.19 million m³

Class C = 2.34 million m³

It was found that three distinct zones could be identified. Zone 1 is comprised of Class A material only. Zone 2 is Class A material overlain by Class C. Zone 3 is Class B material overlain by Class A material. The dump was subsequently instrumented to monitor oxygen concentrations and temperatures, particularly within Zone 2 where the “C-Zone” is best exemplified.

The gas pressure and temperature monitoring system was recommended as a means of better characterizing current oxidation patterns. Eight holes were drilled for instrumentation. A ninth hole was drilled and sampled to fill a gap in the geochemical information, but was not instrumented. Cuttings from all drillholes were sampled over 2 m intervals and submitted for chemical analysis.

The location of the instrumented drillholes and the installation of the instrumentation closely followed the recommendations of an earlier study (SRK, 1995) that included review of other similar installations. The result is a high quality system capable of monitoring temperature, oxygen concentrations, and air pressure at several intervals within each drillhole, as well as providing access for gas sampling and other experimental procedures that may be desirable in the future.

Complete results from a full year of monitoring system were presented in German in SRK (1997). English language papers presenting portions of the data include Smolensky *et al.* (1999) and Lefebvre *et al.* (1999).

Oxygen profiles indicated the influence of several oxygen transport processes. Oxygen enters the pile as a result of diffusion, changes in barometric pressure (barometric exchange), and thermal convection. The strength of some of these processes is evidence that the current cover is ineffective in reducing oxygen penetration. In contrast, temperature profiles within the monitored drillholes were very stable and well suited for quantitative analysis. The temperature profiles were used as a basis for simple heat transfer calculations. Since pyrite oxidation is an exothermic process, it was possible to use the heat transfer calculations to quantify oxidation rates. Temperatures in the pile were generally lower than expected from experience elsewhere, and the estimated oxidation rates were also relatively low.

Figure 7.1 summarizes the oxidation rates calculated from the heat transfer method. The results also provide an indication of where oxidation is occurring within each profile. Comparison of the heat source locations with geochemical data suggests that oxidation is generally restricted to areas that are either already acidic or that contain enough carbonate mineral to neutralize future acid generation

Drillholes 38, 39 and 41B (see Figure 7.1) were located in areas where Class C material was thought to overlay Class A material. The geochemical analyses of drillhole samples confirmed the presence of Class A material at depth in all three drillholes. A nearly continuous 20 m layer of Class C material was found in Drillhole 41B, and was interrupted by only one interval of high sulphide material. In Drillhole 39, the upper 26 m were uniformly Class B material. In Drillhole 38, the upper 12 m were a mixture of Class A, B and C material, but all of it was low in sulphide. The geochemical data collected from the instrumented drillholes indicate that the zone of Class C material that covers much of the Nordhalde is not as continuous or as uniform in NP:AP

characteristics as was thought. However, there is still clearly a layer of non-acid generating material over the more problematic moderate to high sulphide Class A material.

The estimated pyrite oxidation rates in the three “C-Zone” drillholes were from 1.2 to 1.8 kg Py m⁻² yr⁻¹. These values are only slightly lower than the oxidation rates estimated for Drillholes 36 and 37, where continuous Class A material was encountered. It is interesting to note that oxidation areas were generally in material that is moderate to high sulphide, (i.e. greater than 0.5% sulphide S). When this material is further from the surface, the effect is slightly slower oxidation rates.

A more significant effect of the “C-Zone” can be seen by comparing the location of the heat sources with carbonate content. The comparison indicates that oxidation in Drillholes 36 and 37 occurs in intervals where there are no carbonate minerals to neutralize the resulting oxidation products. In contrast, oxidation in Drillholes 38, 39 and 41B occurs in intervals where there is at least some, and often a substantial amount of, carbonate minerals. This, in fact, is the intended function of the “C-Zone”, to restrict oxidation to material that will not generate acidic drainage.

The presence of the carbonate minerals at depths where oxidation is occurring would be expected to neutralize drainage water from this portion of the Nordhalde. However, the water quality monitoring data indicates acidic conditions, with pH generally less than 3. A possible explanation is the presence of other oxidation points within the underlying Class A material. These oxidation points were identified as heat sources from the temperature data. The source of oxygen is not clear, but may be attributable to the thermal convection that becomes stronger in the winter months, when the surface of the pile is cooler than the interior. If this explanation is correct, then the poor water quality from this portion of the Nordhalde should be attributed to the lack of physical control on oxygen convection, (i.e. the lack of an adequate cover), rather than to deficiencies in the “C-Zone”.

In summary, the data collected at the Nordhalde indicates that there is a potential to use inorganic (sulphidic) material with a net neutral NP:AP ratio to delay the onset of acidic conditions in material with a lower NP:AP ratio. However, the processes of oxygen transport in an uncovered, or poorly covered, waste rock pile are complex, and may lead to oxygen circumventing the so called “C-Zone”. A combination of soil cover and inorganic oxygen consuming layer, with the cover designed to prevent thermal

convection and provide the primary control on oxygen diffusion, is now being designed and tested for use on the backfilled Lichtenberg Pit.

7.3 Discussion

Inorganic oxygen consuming layers may be well suited to temporarily delaying ARD if, for example, low sulphide waste is placed on top of higher sulphide waste. No foreign material (i.e. soil or organic material) would need to be transported to the site and all of the material would presumably require final remediation. Consequently, unnecessary material handling would be avoided.

The only field investigations of this method have been on a waste rock pile that has only a partial (and unintentional) oxygen consuming layer. The results indicate that oxygen consumption does occur in the neutral material, and does reduce oxidation rates in the deeper acidic material. However, oxygen penetrates to the acidic waste rock in parts of the pile, probably by thermal convection. The investigators in that case have recommended the method be applied only in conjunction with a soil cover that could prevent thermal convection and provide the primary control on oxygen diffusion.

8.0 ORGANIC OXYGEN-CONSUMING COVERS

8.1 Description

Covering acid generating tailings and waste rock with organic material has been proposed as a method of controlling oxygen penetration into the wastes. The organic covers can act as oxygen barriers in two ways:

- by maintaining a layer of saturated material on top of the waste which physically limits the downward movement of oxygen; and
- by consuming oxygen through the decomposition of organic material.

The types of organic matter that have been considered for use as covers include municipal solid waste (MSW) compost, forest industry waste (e.g. bark and sawdust), food industry waste, lime stabilized sewage sludge and peat. All of these materials can hold water in pore spaces. When saturated they act as a barrier to the movement of oxygen into the underlying waste. The amount of water retained varies with the type of material, its compaction, and the obvious effects of precipitation and evaporation. Oxygen is consumed within organic covers by the process of bacterial oxidation of organic carbon.

8.2 Case Histories

Pierce (1992) provides a literature review of the use of organic material as a cover in tailings reclamation. The review focuses on municipal solid waste but also discusses forest and food industry wastes and peat.

The following case histories also deal with organic covers on tailings. No case histories involving organic covers on waste rock were found.

8.2.1 Laboratory Studies, Ontario

Falconbridge Ltd. and Lakefield Research have tested different cover materials in the laboratory. Stogran and Wiseman (1995) compared covers composed of peat, lime-stabilized sludge and compost on tailings and pyrrhotite concentrate. Oxidized tailings exhibiting low pH and high dissolved metals content were placed in boxes of PVC and plexiglass, then covered with one of the following materials:

- peat;
- lime stabilized sewage sludge (LSSS);
- desulphurized tailings; or
- municipal solid waste (MSW) compost.

Simulated rainfall at a pH of 4.2 was added at a rate that approximated the average annual precipitation rate at Sudbury, Ontario. Samples were collected and pH, sulphate, total sulphur, total iron, ferric iron, ferrous iron, total phosphorous, nitrates, nickel, copper and lead levels determined. Temperature, Eh, oxygen concentration and moisture were monitored in-situ. Data was collected on “rainfall” application, pan evaporation, free drainage and vacuum drain water volumes to allow a water balance to be completed. Elliott *et al* (1997) provides further details on the materials and methodology.

The results from the study after one year indicated that the lime stabilized sewage sludge and desulphurized tailings had the largest effect on the tailings porewater quality. Both cover materials consistently maintained a degree of saturation greater than 90%.

The sample covered with lime stabilized sewage sludge exhibited an increase in porewater pH from 3.5 to 6.1, a decrease in sulphate concentrations, a two order of magnitude increase in dissolved organic carbon concentrations and an order of magnitude decrease in dissolved iron concentrations. Oxygen concentration also decreased from 21% to less than 1%. Sulphate, iron and nickel loadings from the tailings covered with lime stabilized sewage sludge were approximately 45%, 22% and 2%, respectively, of the loadings found in the control cell (uncovered tailings). A black band approximately 0.6 metres thick was observed at the LSSS cover/tailings interface.

The reduced oxygen concentrations in the LSSS cover were concluded to be due to both the high degree of saturation, resulting in a physical barrier to oxygen transport, and to oxygen consumption by organic matter decomposition. The rise in pH was attributed to alkalinity leaching from the cover (the initial pH of the LSSS was 12). The black band visible at the cover/tailings surface was interpreted as caused by metal sulphide precipitation. The presence of dissolved organic carbon (presumably organic acids) in an anoxic environment enhances sulphate reducing bacteria activity. These bacteria catalyse metal sulphide precipitation.

The desulphurized tailings covered tailings exhibited relatively constant porewater pH, an increase in sulphate concentrations, no change in dissolved organic carbon concentrations and an increase in dissolved iron concentrations. Oxygen concentrations decreased with depth, but remained approximately 5% near the cover/tailings interface. The oxygen measured at depth and the increase in sulphate and iron levels indicate that the desulphurized tailings did not completely prevent oxygen entry or oxidation. During the course of the test, cracks were observed in the cover. These cracks may have acted as a direct pathway for oxygen entry into the underlying tailings.

The remaining cover materials (municipal solid waste compost and peat) did not have a significant impact on the chemistry of the tailings porewater. Parameter levels remained relatively constant between the time of test initiation and one year. Also, the parameter levels were similar to those measured in the control cell (uncovered tailings). However, all covered tailings cells exhibited some reduction in sulphate, iron and nickel loadings compared to the control cell.

8.2.2 East Sullivan Mine Tailings Impoundment

Organic covers consisting of various forestry wastes have been placed on the tailings impoundment at the East Sullivan Mine. The tailings impoundment at the mine covers 137 hectares and varies from 2 to 11.5 metres thick. The impoundment dikes were built with tailings and extended as required. An additional 68 hectares is covered by a thin layer of tailings that spilled from the impoundment. The impoundment is underlain by a peat bog with a maximum thickness of 1 metre. Clay underlies the peat.

The East Sullivan deposit was hosted primarily in altered Archean rhyolites, andesites, tuffs and volcanic agglomerates. Sulphides were found in a series of massive subvertical lenses. The sulphide minerals found in the ore include pyrite, chalcopyrite, sphalerite, galena, arsenopyrite, pyrrhotite and marcasite. The tailings, therefore, likely contain high concentrations of arsenic and iron sulphides with appreciable amounts of base metals.

The tailings grain size varies from approximately 50% silt and clay in the centre of the impoundment to coarse sand near the edges. The tailings are oxidized to a depth of 40 cm in the fine material and to more than one metre in the coarser tailings. Acid generation from the tailings was first noticed in the late 1970's. The pH of the material in 1990 was between 2.9 and 3.5 (Tremblay, 1994).

Organic materials have been disposed of in the tailings impoundment since 1984. The organic materials included bark, fibreboard, pulp-wood and sanding dust, with the cover thickness reaching 8 metres in places. In 1990, the amount and composition of the wood waste was restricted due to frequent fires caused by thicker layers. Two metres of organic material waste, consisting of 85% bark, 10% pulp-wood and 5% sawdust and sanding dust, were applied evenly across the site using a bulldozer. The waste was then covered by sewage sludge incorporated into the top 30 cm of wood waste and seeded with grass.

The planned reclamation of the tailings pond at the East Sullivan mine has three phases:

- construction of a water tight dike downgradient from the tailings dam;
- covering of the tailings management area with an organic waste and establishment of vegetation; and,
- construction of a water treatment system.

Construction of the dike began in 1992. The dike was constructed around the existing tailings dam, encompassing the waste materials that have spread beyond the pond. The dike contains a liner of bentonite anchored into the clay located underneath the peat layer below the tailings impoundment. The area between the dike and the original tailings dam will be designed as a wetlands. For additional information, the reader is directed to Tassé *et al* (1997).

The East Sullivan tailings and organic covers have been investigated in several studies. For example, in 1990, a regular program of surface water sampling was completed. During this time, the pH of the tailings material was between 2.9 and 3.5. Metals concentration, summarized in Table 8.1, greatly exceeded the limits defined by the provincial government.

TABLE 8.1
Measured Metal Concentrations in East Sullivan Surface and Interstitial Water

Parameter	Provincial Limits (mg/L)	Surface Water (mg/L)	Interstitial Water (mg/L)
Zn	0.5	270	23
Fe	3	1100	3200
Cu	0.3	29	261
SO ₄		-	13500
Suspended solids	25	7290	-

In 1991, the Ministère des Ressources Naturelles du Québec (MRN) initiated a program to evaluate the effectiveness of the organic cover that had been created up to that time. A series of piezometers and thermocouples (116 in all) were installed in the covered and uncovered tailings. Samples were obtained for pH, metals concentration and gas content. The results showed generally neutral pH in the covered tailings. In contrast to acidic pH values measured in the same area in 1988 and in uncovered tailings sampled in 1992. The metal content of the interstitial water displayed a similar trend (Tremblay, 1994). Zinc concentrations decreased from 30 mg/L in 1988 to less than 3 mg/L in 1991.

An additional six test plots were constructed in by INRS-GeoRessources in 1994 to assess the effectiveness of conifer bark covers on the water quality from fresh and oxidized tailings. The test plots were constructed in a section of the pond that had not been covered by wood waste. The plots measured 20 metres by 20 metres with 5 metres between each plot. A synthetic liner was installed on three sides of each plot. A geotextile drain channeled flow from the south side.

Six test plots, each measuring 10m x 10m each were set up by the Centre de Recherches Minerales du Québec (CRM) and monitored from 1992-94. The plots tested the following:

- uncovered oxidized tailings
- uncovered fresh tailings
- 1 metre of conifer bark over oxidized tailings
- 1 metre of conifer bark over fresh tailings
- 2 metres of conifer bark over oxidized tailings

- 1 metre of conifer bark over oxidized tailings, with 30 cm of sewage plant sludge at the surface

A nest of piezometers and a thermocouple were installed in each test plot such that samples for physico-chemical analysis could be obtained from various levels. In addition to the interstitial water, the interstitial gas was also sampled and analyzed.

Results of the gas profile sampling in the organic covers displayed consistent trends. Oxygen concentration decreased to less than 3% within one metre or less of the cover surface, and carbon dioxide and methane concentrations increased (up to 50% and 45%, respectively). It is clear from these results that the organic cover effectively restricts oxidation of the underlying tailings. The low oxygen concentrations and high carbon dioxide and methane concentrations were observed, even though the forestry wastes are relatively permeable, shows that oxygen consumption is the active mechanism. (Tremblay 1994, Tasse *et al.* 1997)

Total reclamation costs for the East Sullivan impoundment are estimated to be 7.5 to 8 million dollars. This sum includes construction of the water tight dike, the water treatment facility, water disposal and tailings study. It also includes construction of a wetlands area between the existing tailings dam and the water tight dike. The authorities hope this wetlands area will provide a “walk away” solution, eliminating the need for active water treatment. The organic cover was installed at essentially no cost to the mine. Both the bark and the sludge were transported to the mine site and placed on the tailings at no expense to the mine.

8.3 Discussion

The case histories indicate that organic covers on tailings can effectively minimize the amount of oxygen reaching the tailings. Some questions remain about the use of organic covers on tailings. Tasse *et al* (1997) mention the possible chemical reduction and dissolution of iron hydroxides and other metal co-precipitates, and the chelation of metals by organic acids. Although there was no strong evidence for either effect in the East Sullivan data, these possible complications have not been ruled out. The life expectancy of the cover is dependent largely on the rate of decomposition. The relationship between rates of degradation and long term cover performance has not been established. Whether the function of an organic cover is blocking or consuming oxygen, the cover must remain moist. Therefore, use of these covers is limited to areas with moderate to high rainfall conditions throughout the year.

The use of organic covers as a method to delay the onset of acidic drainage has not been tested. However, it is clear that if oxygen entry to the mine waste can be prevented, then the onset of acidic drainage would be delayed.

A greater limitation is the fact that none of the tests or case histories applied organic covers on waste rock. Transfer of the method to waste rock will need to take into account the significant differences in geometry and grain size. Whereas tailings are generally deposited in a flat pond, waste rock is generally placed in piles with exposed sides. Constructing a stable cover on the side slopes of a pile is much more difficult than constructing a cover on a flat area. The simple dumping of large depths of organic matter, such as in the East Sullivan case history, would not create a stable cover on a waste rock pile. In addition, the side slopes and the coarse grain size of waste rock allows air flow into the piles, which makes it harder to consume oxygen in a relatively thin cover layer.

Given these complexities, it may be more appropriate to incorporate an organic layer within a waste rock cover system. Pierce (1992) outlined two models for organic covers. In one model, a layer of overburden covers the organic layer. The overburden layer protects the organic layer from erosion and decreases evaporative water loss. In addition, the weight of the overburden compacts the organic layer. The second model has a coarse layer acting as a capillary break, preventing water from draining from the organic layer.

The cost of organic covers depends largely on the proximity of the source of the organic material. Nearby sources of wood waste or peat may make organic covers a viable reclamation option. The use of municipal wastes may also be financially attractive, as many municipalities pay for its disposal.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions Regarding Effectiveness of Individual Methods

This review clearly shows a lack of well-designed and documented case studies of methods to delay the onset of acidic drainage. The following conclusions are therefore stated cautiously.

Bactericides have been shown to inhibit the onset of ARD in coal wastes at reasonably low cost. However, there has been no well-designed, monitored and documented study of this technique to prove its usefulness and cost on metal mine waste.

The use of phosphate to armour sulphides has met with only limited success in laboratory studies and has not been tested in field trials. Phosphate addition is likely to be expensive for use as solely as a method to delay acid generation.

Lime or limestone addition is clearly capable of neutralizing acidity that has already been generated. However, the method needs to be carefully designed to ensure adequate mixing of the alkali with the acidic material, and to take into consideration (site specific) variations in acidity. The effectiveness of lime or limestone addition as a means to delay the start of acid generation has not been tested.

There is strong evidence that soil covers can reduce the penetration of oxygen into waste rock. Although most field trials have involved covering waste that is already acidic, it is a safe assumption that limitations to oxygen transport would also limit the initial development of acidic conditions. For covers to be effective as oxygen barriers, they must be well engineered and constructed. The cost may be high for use as a temporary delay method.

Initial research into the effects of freezing or permafrost on slowing ARD has had positive results, but no well-documented field trials have been completed.

Field investigations of an inorganic oxygen-consuming layer are underway at one site in Germany. The results are favourable but difficult to extrapolate to other sites. Site-specific field and laboratory trials would be needed before this method can be reliably implemented at other sites

Organic covers have been shown to limit rates of acid generation in tailings, but has not been tested on waste rock. Some of the limitations observed in the tailings tests, such as difficulties in keeping the organic layer in place and adequately moist, could be more severe in waste rock applications.

9.2 Recommendations for Further Studies

With the possible exception of soil covers, there is no proven methodology for *a priori* design and evaluation of methods to delay the onset of acidic drainage. Site specific trials will be needed for all applications. Table 9.1 lists the issues that should be taken into consideration when these trials are being designed. Attention to the listed issues will make the results of each set of trials as definitive as possible, and will lead to results that will be as applicable to other sites as possible.

In the authors' opinions, methods that warrant coordinated research include:

- Bactericide application (on metal mine rock);
- Alkali addition (as a delay method);
- Soil covers (as a delay method);
- Inorganic oxygen-consuming covers;
- Organic oxygen-consuming covers; and,
- Freezing/permafrost.

A well-designed field study of bactericides is needed to demonstrate whether this method can be effective in metal mine waste. Alkali addition and soil covers are clearly effective for dealing with waste that is already acidic, but their effectiveness as delay methods needs to be demonstrated. Organic and inorganic oxygen-consuming covers are potentially inexpensive cover options and should be tested under field conditions. Low temperatures have been shown to slow ARD; this field of research should be expanded to determine the long-term effects and the possible benefits of depositing waste into a permafrost setting. The issues listed in Table 9.1, should also be considered in the design of the coordinated research projects.

TABLE 9.1
Issues to Consider When Assessing Delay Methods

TECHNIQUE	ISSUES
General	<ul style="list-style-type: none"> • Preliminary laboratory tests to optimise addition rates etc., and to identify the mechanisms involved, are strongly recommended • Tested material needs to be sufficiently characterized and demonstrably representative. Includes both waste and any additives • Water quality monitoring is necessary but not sufficient (may not change for a long time after method implementation, especially if there are oxidation products already stored in the waste). • Immediate measurements of oxidation rates, i.e. oxygen and temperature monitoring, are preferable. • Need post-mortem to investigate storage of oxidation products and other effects not noticeable in discharge water. • Complete monitoring and/or control of water balance strongly preferred (i.e. all inputs and outputs). Monitoring stations should be influenced only by the waste pile being assessed. Background data should be collected from the monitoring stations prior to tests. • Experimental control (i.e. untreated waste) must be set up and monitored exactly the same as method test. • Engineering and cost data should be collected and reported. Estimated costs for delay method should be compared to costs of dealing with acidity after it has formed, (e.g. by alkali addition).
Bactericide	<ul style="list-style-type: none"> • Need preliminary laboratory tests to select and quantify bactericide. Understanding of mechanism is essential to design of test program. • Monitor bacterial populations, MPN, and speciation. • Monitor for downstream bactericide. • Evaluate distribution of bactericide within pile. • Consider effects of inorganic oxidation (monitor pH and oxygen consumption).
Phosphate	<ul style="list-style-type: none"> • Need preliminary laboratory tests to select and quantify phosphate additive, and to define mechanism by which it functions. • Assess spatial variability and distribution of phosphate sources and secondary phases. • Need petrographic studies before and after treatment to confirm the presence of coatings.
Alkali Addition	<ul style="list-style-type: none"> • Laboratory tests to estimate alkali requirements are advisable. • Assess spatial variability and distribution of alkali. • Need petrographic studies to indicate whether sulphide minerals and/or alkali sources are armoured by secondary hydroxides. • Monitor bacterial population to indicate neutral pH effects on oxidation rate.
Low Permeability Covers	<ul style="list-style-type: none"> • Complete water balance is necessary. • Monitor the cover water content. • Oxygen monitoring within pile is necessary. • Determine the oxidation rate after cover installation. • Scale effects are important. Construction defects and disturbances due to settlement are examples of phenomena that would not be observable in very small scale tests. • Seasonal effects are important. Wetting/drying and freeze/thaw effects are examples.
Freezing/ permafrost	<ul style="list-style-type: none"> • Monitor temperature and moisture content. • Difficult to create true controls on site. • Seasonal effects are important.
Inorganic O ₂ -consuming covers	<ul style="list-style-type: none"> • Monitoring of oxygen concentration and temperature is essential both in the cover and in the waste rock pile. • Scale and time effects are important. Oxygen transport mechanisms change if pile is large enough, and if duration is long enough, for pile temperatures to increase.
Organic O ₂ -consuming covers	<ul style="list-style-type: none"> • Monitor concentration of oxygen, carbon dioxide and methane in the cover and in the waste rock pile. • Monitor moisture content of the cover.

- | |
|---------------------------------------------------------|
| • Seasonal effects, (wetting and drying) are important. |
|---------------------------------------------------------|

9.3 Concluding Note

Many studies have been conducted or are in progress on both permanent and temporary methods to delay ARD, but were not available for review. Knowledge of these tests and their results remain with the personnel of the companies that conducted them.

The authors acknowledge the limitations of the information presented herein and hope that this report will encourage publication of additional data, and enhance the design of future test programs. Both are needed to develop and demonstrate effective methods to delay the onset of acidic drainage.

This report, **Review of Methods for Delaying the Onset of Acidic Drainage - Case Studies**, has been prepared by:

STEFFEN, ROBERTSON AND KIRSTEN (CANADA) INC.

Daryl Hockley, P.Eng.

Tracy Delaney, P.Geo.

Diana D. Sollner, P.Eng.

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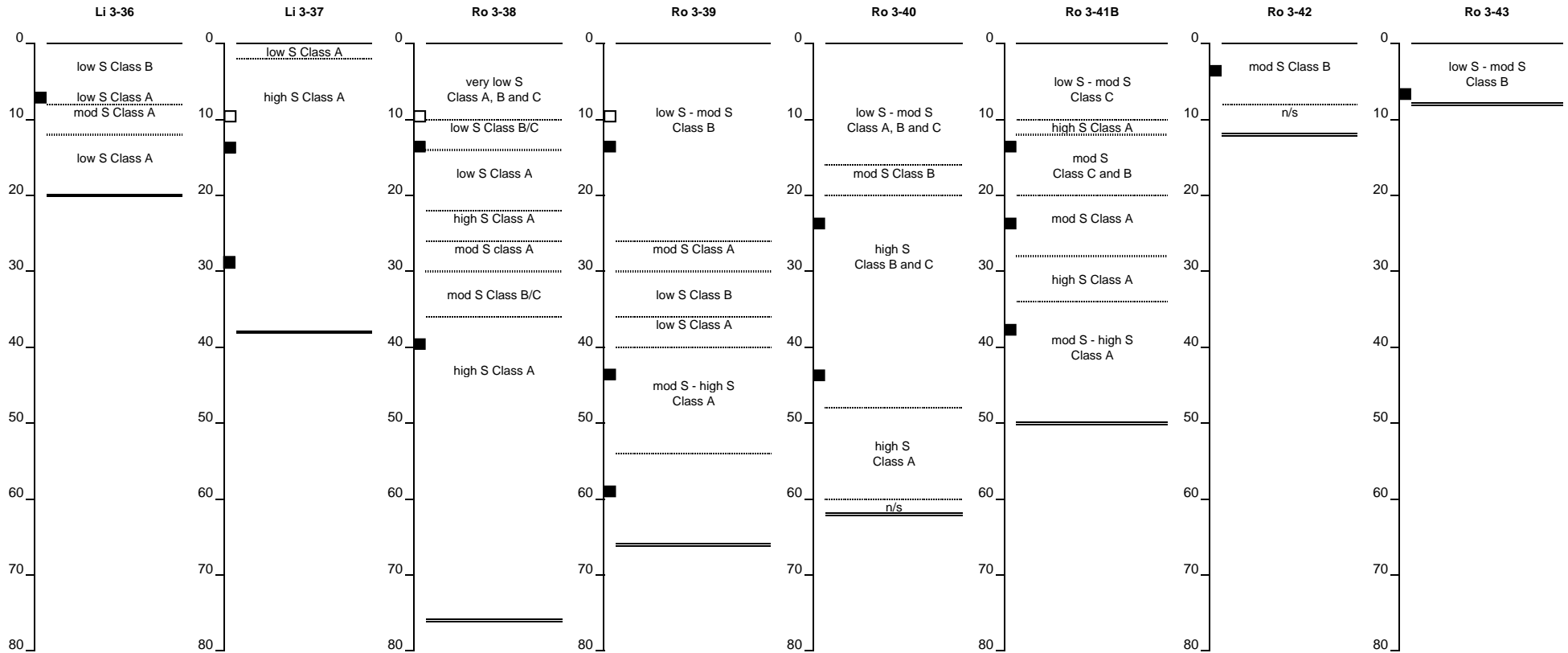
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FIGURES

FIGURE 7.1 Summary Logs



Heat Source

Oxygen Sink

APPENDIX A
Minutes of Teleconference



STEFFEN ROBERTSON AND KIRSTEN (CANADA) INC.

Suite 800, 580 Hornby Street, Vancouver, B.C. Canada V6C 3B6
Phone: (604) 681-4196 Fax: (604) 687-5532

FAX TRANSMITTAL


FAXED

PAGE 1 OF 5
(including transmittal)

PROJECT NO.: P118101
DATE: January 22, 1996
TIME:

HARD COPY TO BE MAILED YES NO

TO: Gilles Tremblay	CANMET	Ottawa	613-996-9673
Bill Price	MEMPR	Smithers	604-847-7603
Peri Mehling	Mehling Environmental Mngt.	Vancouver	604-731-4150
Andy Robertson	Robertson Consultants Ltd.	Vancouver	604-687-5532
Paul Ziemkiewicz	Natl. Res. Center for Coal & Energy	Morgantown	304-293-7822

FROM: Tracy Delaney 

RE: **Summary of Teleconference on the Temporary Delay of the Onset of Acidic Drainage, January 15, 1995**

Attendees: Gilles Tremblay
Bill Price
Paul Ziemkiewicz
Peri Mehling
Andy Robertson
Daryl Hockley
Tracy Delaney

INTRODUCTIONS

OVERVIEW

BP - Current mine permitting applications contain measures for dealing with potentially acid generating material. However, at many sites final remediation of waste material must be delayed while mining is completed. In such cases temporary measures for delaying the onset of ARD are required. Therefore, the objective of this project is to review case histories of the different methods available.

Primary objective of the project:

Review case histories of remediation measures where there is a delay before final remediation, such as at the Huckelberry Mine where deposition of waste underwater must be delayed until mining is completed. Provide what detailed information of each case study, is available, as well as document what information is unavailable. Be critical of the information received.

Secondary objective:

Identify omissions so that MEND can plan the next phase of studies.
Identify any proven delay measures and any that should not be considered further.

This project should not address research on blending and layering, as these fall into the study being conducted by Peri.

DH - How is delay currently incorporated into permit applications in B.C.?

BP - Requires thorough provision for collection and treatment. Examples:

Huckelberry - returning waste to pit, then flooding. They estimate that it will be 5 years before they begin backfilling and 10 years for flooding to be complete.
- proposing till covers
- government looking at Heath Steele type cover but would like to look at cheaper options.

Eskay - addition of lime to waste rock only delayed acid drainage; not permanent as was hoped. This was largely because of the manner in which the lime was applied. They have ended up collecting and treating.

Appalachians - many situations where delay techniques have been applied. Permanent solutions turn out to be temporary.

Cinola - testwork done.

QR and Kemess - interesting but only as proposed mines, not as case histories.

Stratmat - laboratory study and field application. Mixing of lime with waste rock prior to backfilling the pit was unsuccessful in delaying ARD.

GT - Want to be sure that for both MEND projects the information in the case studies is subject to review by the company supplying the information prior to publication.

REVIEW OF MEASURES**Bactericide application**

GT - Sudbury '95, Pittsburgh '88

PZ - Tried by many coal companies. Experience indicates that this method fails after a few months to 5 years. Therefore, a temporary delay. Studies done on 400 tonne piles of pyritic shale.

PM - Equity Silver used on the haul road

PZ - Al Meek (Lexington, KY), Island Creek Coal Co. tried several technologies. Compared caustic soda consumption. Look in Pittsburgh Conf. Vol. II

AR - Appears to work best in fine-grained material due to lateral movement of groundwater.

PZ - no change in sulfate release but did neutralize acidity, pyritic shales.

GT - Pitts. '88 - Rustogi

- lots of coal companies bought into the idea and tried it out

AR - B.F. Goodrich - produced much of the bactericide. Call them to find out who they sold it to and location of best results.

PZ - Bob Klineman - U.S. Bur. of Mines (412) 892-6555, Pitts. Res. Centre

Phosphate application

GT - Margaret Kalin - Inco, Denison Mine; formation of a surface coating.

- will provide names of individuals in field.

BP - See literature review by B.C. Research on lime and lime phosphate.

- One on Kennecott's Chino Mine (now Cyprus)

AR - project of Gultekin Savci in SRK's Denver office.

GT - Ontario government has not pursued this method much because of the high cost of transportation.

PZ - paper on phosphates at Island Creek in Pittsburgh Conf. Vol. Phosphate behaved like lime in forming precipitates.

- does not believe in phosphate coatings

- Bill Evangelou tried hydrogen peroxide and phosphate

- 5-6 times more expensive in their area

GT - MEND Quebec - Fytas, prof. at Laval U., presented paper at conference.

TD - will followup with GT.

Irrigation with Alkali

Cinola - blending

New Brunswick Coal - lime treated sludge

Minto? - Michelle Coleman (506) 327-2240 Gilles will send info.

Joe Duncan (304) 393-5603 - W. Virginia conf., April '95. Ammonia treated sludge being pumped to the top of waste pile.

Carrucio, 1985. Look in Wismut report. Joe Duncan reactivating this work.

GT - two reviews of case histories currently being completed. In-pit disposal and material placed below the water table. Gilles will send copies of these.

Commercial Reactor Inhibitors

DH - Meant chelating. Probably a better term.

- looked at this in Wismut project but the chelated metal compounds are a problem.

- Probably not a viable alternative but should summarize promotional literature. Provide report users with the info. that this method not yet tested.

AR - Like to mention three other temporary methods that are not on the list.

Freezing

AR - Important in B.C. where freezing often sited as the solution to ARD problems.

GT - MEND review (DIAND). Gilles will send copies.

Bill Napier - Golden Lake

Agra - Richard Dawson (Calgary) and Kevin Morin. Looking at use of permafrost as control of ARD.

BP - Recommend include a brief overview and reference to other studies.

Very Dry Areas

AR - no acid generated in very dry locations

GT - Not directly applicable to Canada.

TD - but Canadian Co.s working in these areas

GT - MEND mandate is Canadian applications. Therefore, brief overview only.

Sites - Escondida

Africa (AMR)

Key Lake

Control Water Balance in the Dump until Final Deposition

Included in items above and below.

Soil Covers

AR - migration and oxygen control

- Wismut

GT - U. of Sask. - Lee Barbour conducting review of covers.

- Noranda Heath Steele

- Golden Sunlight, Patricia

- Equity Silver

- will provide info.; provide contacts.

- Senes - identifying other material to be used: MEND report 220.1

GT - Westmin - shotcrete and cementation

BP - emphasized performance of cover not of pile

- only small portion of dump covered

Oxygen-consuming Organic Covers

GT - Tailings

Lakefield Res.

wood waste covers - Sullivan?

Noranda Tech. Center - waste rock; final report avail.

AR - Wood waste (Sweden); Fallin

- Norwegian Technical Inst. - slurried sludges. Tom Lungren

GT - Compost study

- Bob McCludy, Falconbridge outside Sudbury
- Pierce at Laurentian U.
- Literature review

DH - USBM

GT - Might look at MEND annual report and see if there are reports that would be useful. Get them from Gilles.

Inorganic oxygen -consuming covers (C-layer concept)

Long discussion on how to coordinate with Peri's work. Both will discuss it as it applies to each topic but projects will share information so as not to duplicate effort.

Information to be collected

Important to document what was not collected at each place and note this in the report.

GT - two Senes reports: in pit disposal and material below the water table.

David Drava, Senes - (905) 764-9380, (905) 764-9386 FAX. Contact for ideas on what info. to collect.

- will send copies to SRK when available.

Closing Comments

AR - Suggest Peri and Tracy put a request for information on Info-Mine to get input.