SESSION 1: CONTAINMENT AND MITIGATION OF TOXIC MINE WASTE

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OXYGEN TRANSPORT AND PYRITE OXIDATION IN UNSATURATED COAL-MINE SPOIL[1]

by

Weixing Guo[2] and Charles A. Cravotta III[3]

Abstract. An understanding of the mechanisms of oxygen (O_2) transport in unsaturated mine spoil is necessary to design and implement effective measures to exclude O_2 from pyritic materials and to control the formation of acidic mine drainage. Partial pressure of oxygen (Po_2) in pore gas, chemistry of pore water, and temperature were measured at different depths in unsaturated spoil at two reclaimed surface coal mines in Pennsylvania. At mine 1, where spoil was loose, blocky sandstone, Po_2 changed little with depth, decreasing from 21 volume percent (vol %) at the ground surface to a minimum of about 18 vol % at 10 m depth. At mine 2, where spoil was compacted, friable shale, Po_2 decreased to less than 2 vol % at depth of about 10 m. Although pore-water chemistry and temperature data indicate that acid-forming reactions were active at both mines, the pore-gas data indicate that mechanisms for O_2 transport were different at each mine. A numerical model was developed to simulate O_2 transport and pyrite oxidation in unsaturated mine spoil. The results of the numerical simulations indicate that differences in O_2 transport at the two mines can be explained by differences in the air permeability of spoil. Po_2 changes little with depth if advective transport of O_2 dominates as at mine 1, but decreases greatly with depth if diffusive transport of O_2 dominates, as in mine 2. Model results also indicate that advective transport becomes significant if the air permeability of spoil is greater than 10^{-9} m^2, which is expected for blocky sandstone spoil. In the advective-dominant system, thermally-induced convective air flow, as a consequence of the exothermic oxidation of pyrite, supplies the O_2 to maintain high Po_2 within the deep unsaturated zone.

Additional Key Words: advection, diffusion, numerical simulation, heat transfer

Introduction

Atmospheric oxygen (O_2) is required for pyrite oxidation and the consequent formation of acidic mine drainage (AMD). Gaseous or dissolved O_2 is necessary for the direct oxidation of pyrite and for the regeneration of ferric iron (Fe^{3+}), which is an important oxidant (Singer and Stumm 1970). Hence, an understanding of the mechanisms of O_2 transport in mine spoil is necessary to design and implement effective measures to control the formation of AMD.

Pyrite oxidation takes place mainly in the unsaturated zone of mine spoil. Although infiltrating water carries some dissolved O_2 into mine spoil, gaseous transport of O_2 generally is more effective than aqueous transport of O_2 because of the low solubility and low diffusivity of O_2 in water (Watzlaf 1992).

Gaseous O_2 transport through air-filled voids in spoil involves both processes of diffusion and advection. Diffusive transport is the movement of O_2 molecules from zones of high O_2 to zones of low O_2 concentration. Steep gradients in O_2 concentration can be formed between the exterior and interior of spoil because of relatively rapid O_2 consumption by oxidation reactions and slow diffusive transport of O_2. If air permeability is low, such as in compacted, shaly spoil, diffusive transport can be the major mechanism

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of O_2 transport. However, if air permeability of spoil is high, such as in blocky sandstone spoil, advective transport of O_2 by moving air can predominate. Thermal gradients within spoil can induce the inward (lateral) flow of oxygenated air to replace outward (upward) flowing air that is warmed by the exothermic oxidation of pyrite (Harries 1969). Advective transport can also result from rapid changes in barometric pressure and from displacement of air by ground water.

Approaches to controlling the formation of AMD include minimizing the exposure of pyrite to fresh air and oxygenated or Fe^{3+}-rich waters (Kleinmann and Erickson 1986; Barton-Bridges and Robertson 1989; Watzlaf 1992). However, the processes that form AMD in unsaturated spoil are complex and involve many hydrological, chemical, and biological factors (Williams et al. 1982). Numerical models have been developed to evaluate the interactions of these factors and the generation of AMD (Cathles and Apps 1975; Jaynes et al. 1984a,b; Pantelis and Ritchie 1992).

In this study, evaluations were made on the relative importance of diffusive and advective transport of O_2 on the distribution of O_2 in coal-mine spoil and the effect of O_2 supply on the formation of AMD. Composition of pore gas, temperature, and water quality were measured at different depths in spoils at two reclaimed surface coal mines in Pennsylvania. A two-dimensional numerical model that was developed to study the relation between O_2 transport and the rate of acid generation (Guo 1993) is used to explain the observed chemical compositions of pore-gas and pore-water samples from the mines.

Field Studies of Oxygen in Mine Spoil

The availability of O_2 in mine spoil is controlled by the dynamic balance between the rate of O_2 consumption and the rate of O_2 supply. Consumption of O_2 results from pyrite oxidation, biological respiration, and other reactions. The rate at which O_2 is replenished at reaction sites is controlled largely by the air permeability, moisture content, temperature, the O_2 partial pressure (Po_2) gradient, and the strength of air convective flow within surrounding spoil. Therefore, the availability of O_2 in mine spoil can vary spatially and temporally.

Field investigations of O_2 in unsaturated spoil have been conducted at several surface coal mines in western Pennsylvania. Although active pyrite oxidation and AMD were problems at all these mines, the spatial distribution of Po_2 in pore-gas samples was extremely variable among and within the mines. Jaynes et al. (1983) reported fairly high Po_2. Po_2 in several boreholes decreased from 21 vol % at the ground surface to greater than 10 vol % at a depth of 12 m. At a second mine, Fielder (1989) reported Po_2 as high as 15 vol % down to 9.1 m; however, in adjacent spoil containing pyritic refuse, Po_2 was less than 1 vol %. At another mine, Lusardi and Erickson (1985) reported annual mean values of Po_2 as low as 1.3 vol % and as high as 10.2 vol % at a depth of 4.6 m in different boreholes. Data for two additional mines that were collected by the authors are representative of these extreme ranges and are described below.

Mine 1. Advective-Transport Dominant

Mine 1 is a reclaimed, abandoned surface coal mine on a broad hilltop (40°55'30"N, 78°22'30"W) in southern Clearfield County (Guo 1993). During 1968-85, the lower Kittanning coal was mined. The lower Kittanning coal and a rider seam with associated coaly shale were pyritic and had total sulfur concentrations of 3.8 and 5.4 weight percent (wt %), respectively. Spoil material was predominantly blocky sandstone and siltstone. Many boulder size fragments, with diameters greater than 1 m, were distributed throughout the spoil, and large voids were encountered during drilling. Seepage water in a roadcut along the western boundary of the mine was identified as AMD from the mine.

In 1989, a total of 35 boreholes (2-20 m deep) were drilled

in spoil at the site. A control hole was drilled in an adjacent, unmined area. Piezometers were installed in the boreholes for measurement of the temperature in mine spoil and for ground-water sampling. Nested gas samplers were installed adjacent to the piezometers in 13 of these boreholes. Gas sampling ports were placed at depths of 0.9 m, 1.5 m, 4.6 m, 6.1 m, 9.1 m, 10.7 m, and deeper (Guo et al. 1994). Pore-gas and water sampling were conducted monthly for 1 and 2 years, respectively.

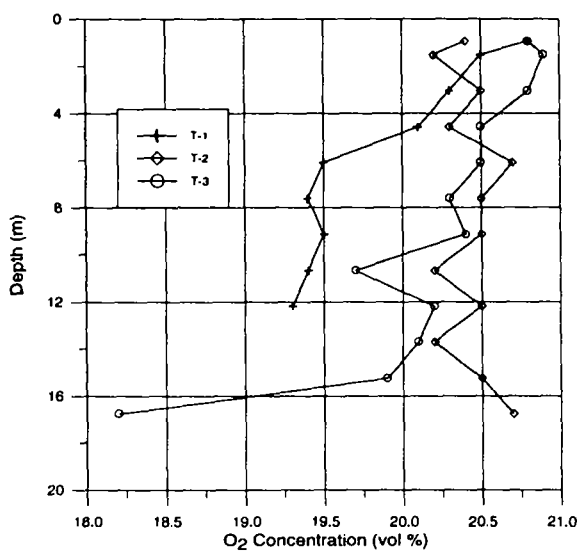

Figure 1. Concentrations O_2 in pore-gas samples from three boreholes (T-1, T-2 and T-3) in unsaturated spoil at mine 1 in Clearfield Co., PA October, 1989.

The chemistry of ground water and seepage water indicates that acid-generating reactions are ongoing at this mine. Water from a perennial seep (N1) had a median pH of 3.4 and had concentrations of sulfate, dissolved iron, dissolved manganese, and acidity, respectively, of 2,200, 45, 52 mg/L, and 290 mg/L as $CaCO_3$ (Durlin and Schaffstall 1993).

Pore-gas O_2 concentrations at mine 1 were found to exceed 18 vol % throughout the spoil during the entire year of monitoring. Several depth profiles of Po_2 are presented in Figure 1. Corresponding low concentrations of CO_2 ranged from 0.03 to 1.2 vol %. The amplitude of seasonal variations in Po_2 and Pco_2 was small.

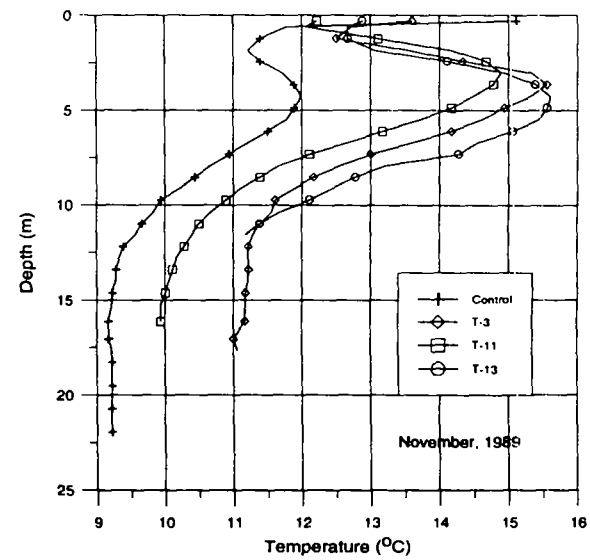

Figure 2. Temperatures in unsaturated spoil at mine 1, November, 1989. Control temperature was measured in a borehole in adjacent unmined area.

Air convection resulting from the temperature gradients induced by the exothermic pyrite-oxidation reactions is the dominant O_2 transport process at this mine (Guo and Parizek 1994). Thermal anomalies were detected in most deep boreholes during the study period. Spoil temperatures were 1-2°C higher than the background temperature measured in the control hole (Figure 2).

Mine 2, Diffusive-Transport Dominant

Mine 2 is a reclaimed surface mine on two adjoining hilltops (41°04'15"N, 79°26'45"W) in southern Clarion County (Cravotta et al. 1994a, b). During 1980-86, the lower Kittanning coal was mined. The lower Kittanning coal and a 1.2-m thick stratum of carbonaceous shale overlying the coal were pyritic, had total sulfur concentrations greater than 2.5 wt % and were laterally continuous across the mine. Spoil at this mine was friable shale with minor siltstone. Spoil fragments generally were less than 10 cm in diameter.

In 1991, a total of 12 clusters of two or more boreholes

were drilled in spoil and underlying bedrock. Several clusters, or monitoring nests, included boreholes for ground-water sampling, pore-water sampling, and pore-gas sampling (Cravotta et al. 1994b). Lysimeters and gas-sampling ports were placed at depths of 1 to 1.5 m, 4 to 4.6 m, 7 to 7.6 m, and 10.7 to 11 m below the spoil surface to enable comparison of chemical concentrations in pore-water and pore-gas samples.

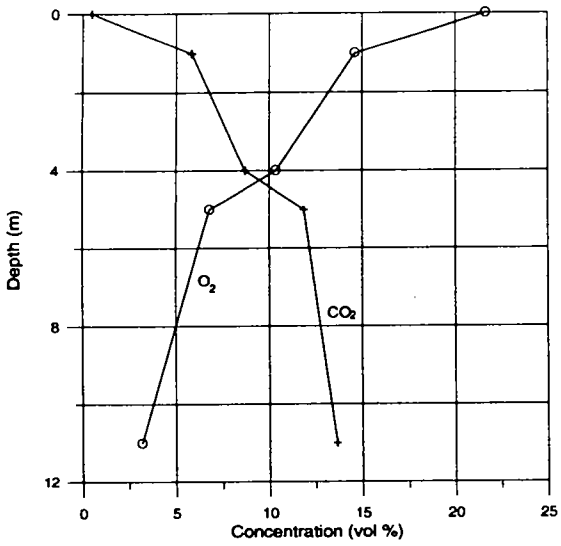

Figure 3. Mean concentrations of O_2 and CO_2 in pore-gas samples from a borehole (Nest 2) in unsaturated spoil at mine 2 in Clarion Co., PA February to December, 1992.

Ground-water samples from the spoil at mine 2 were highly mineralized, with concentrations of sulfate that exceeded 400 mg/L (Lescinsky et al. 1993). Despite this evidence of pyrite oxidation, overall ground-water quality was alkaline because of neutralization by carbonate minerals (mainly siderite) in the saturated zone (Cravotta et al. 1994b). Locally in the unsaturated zone, however, shallow pore water sampled within or near pyritic zones was acidic and had high concentrations of sulfate. For example, in December 1992, pore water sampled from a depth of 4.6 m in the northern part of the mine (nest N2) had pH of 4.0 and concentrations of sulfate, dissolved iron, and dissolved manganese of 5,000, 1.3, and 260 mg/L, respectively.

Data for pore-gas compositions at mine 2 indicate that Po_2 decreases from 21 vol % at the land surface to less than 2 vol % at 10.7 m below the surface, with corresponding increases of Pco_2 with depth (Figure 3). The increase of Pco_2 with depth resulted from the dissolution of carbonate minerals. Because the pore water in spoil is extremely mineralized and dissolved anions are dominated by sulfate, oxidation of organic matter is not considered to be an important control of O_2 and CO_2 at the mine. Cravotta et al. (1994b) concluded that pyrite oxidation rates at mine 2 were controlled by rates of O_2 diffusion and not the amount of pyrite, because concentrations of O_2 declined rapidly at shallow depths in the spoil, independent of pyrite concentrations.

Model Description

A two-dimensional numerical model was developed to investigate the distribution, transport, and reaction of O_2 in unsaturated mine spoil. This model simulates coupled heat transfer and gas flow, dispersive-advective oxygen transport, steady-state ground-water flow, and pyrite oxidation reactions (Guo 1993).

Coupled heat transfer and gas flow in mine spoil are described by the following set of equations:

$$\frac{\partial}{\partial t}(\phi_s \rho_s C_s T + \phi_l \rho_l C_l T + \phi_g \rho_g C_g T) =$$

$$\nabla \cdot (\kappa \nabla T) - \nabla \cdot (\rho_g C_g \vec{v}_g T) - \nabla \cdot (\rho_l C_l \vec{v}_l T) + SS_{energy} \quad (1)$$

$$\phi_g \frac{\partial}{\partial t}(\rho_g) = -\nabla \cdot (\rho_g \vec{v}_g) \quad (2)$$

$$\vec{v}_g = -\frac{k}{\mu_g}(\nabla P + \rho_g \vec{g}) \quad (3)$$

Equation 1 describes heat transfer through solid, liquid and gas phases in spoil; equation 2 represents gas flow through porous medium; and equation 3 is the Darcy law, which links equations 1 and 2. In these equations, ρ is the density $[ML^{-3}]$; C, the heat capacity $[JM^{-1}K^{-1}]$; ϕ, the volume fraction [dimensionless]; T,

temperature [K]; κ, the thermal conductivity of spoil [$JL^{-1}K^{-1}T^{-1}$]; t, time [T]; SS_{energy}, the energy generation and/or consumption rates [$JT^{-1}L^{-3}$] which includes the energy released from pyrite oxidation reactions and the energy transfer due to phase changes; $\vec{v}$, the flow velocity of fluid [LT^{-1}]; g, the gravitational constant [LT^{-2}]; P, the air pressure [$ML^{-1}T^{-2}$]; k, the air permeability [L^2]; and μ, the viscosity of gas [$ML^{-1}T^{-1}$]. Subscripts s, l, and g represent solid, water and gas phases respectively.

To simplify the problem so that it can be solved numerically, several assumptions are made: (1) local thermal equilibrium between all the phases is present at all points, because the temperature difference between the phases generally disappears quickly; (2) thermal conductivity is treated as a constant because the range of temperature changes is relatively small; (3) radiation is negligible; (4) thermal dispersion is insignificant; (5) Darcy's law is valid for gas flow of relatively low velocity, as considered in this study; (6) physical properties of water and solid are constant; (7) gas density is independent of its component composition; (8) air is in equilibrium with pore water and obeys the ideal gas law; and (9) water is assumed to be saturated with respect to the local Po_2 in pore gas in accordance with Henry's law.

Transport of O_2 by dispersion-advection is mathematically described as:

$$\phi_g \frac{\partial C}{\partial t} = \nabla \cdot ([D']\nabla C) - \nabla \cdot (\vec{v}_g C) - \nabla \cdot (\vec{v}_l C) + SS_{oxygen} \quad (4)$$

where C is the concentration of O_2 in air [ML^{-3}]; [D'] is the dispersion coefficient tensor [L^2T^{-1}]; SS_{oxygen} is the source/sink terms including all the O_2 consumed in a unit time inside a block [$MT^{-1}L^{-3}$].

Factors affecting the rate of pyrite oxidation have been expressed numerically by previous investigators using a variety of approaches, of which the shrinking core model is perhaps the most popular one used to simulate pyrite oxidation (Harries 1969; Roman et al. 1974; Madsen et al. 1975; Cathles and Apps 1975; Jaynes et al. 1984a, b). In an unreacted-core model, as used in this study, oxidation proceeds as a narrow front moving into the solid particle and solid reactant concentration remains constant inside the unreacted cores. All the pyrite is assumed to be oxidized in the ash zone outside the unreacted core. Mathematical expressions for these reaction-control mechanisms and for different particle geometry were given by Levenspiel (1972).

Combining of surface-reaction rate and reacted layer diffusion controls gives the reaction rate of a particle containing pyrite:

$$\frac{dN}{dt} = \frac{-1}{\frac{1}{3}\tau_1 N^{-\frac{2}{3}} + 2\tau_2 (N^{-\frac{1}{3}} - 1)} \quad (5)$$

where N is the amount of unreacted pyrite in mole fraction. τ_1 and τ_2 are the time [T] for complete reaction of a particle under surface reaction control and diffusion through ash layer control. Two sets of equations, as defined above, are used to represent the rate of pyrite oxidation by dissolved O_2 and Fe^{3+}, respectively.

Equation 5 defines the reaction rate under non-biological conditions. However, pyrite oxidation can be greatly accelerated by the iron-oxidizing bacterium, *Thiobacillus ferrooxidans* (Singer and Stumm 1970). Increases in pyrite oxidation rates because of biological catalysis are reported to vary from 10 to 50 times (Lorenz and Tarpley, 1963) to 10^6 times (Singer and Stumm, 1970). A simple relation, similar to that given by Jaynes et al. (1984a) is modified and used in this model to account for the activity of iron-oxidizing bacteria.

The mathematical model, described above, was solved using the Newton-Raphson method in a fully-coupled, implicit way based on the block-centered finite difference scheme. Detailed discussion of this model, its numerical procedure, model calibration and testing were presented by Guo (1993).

Results and Discussion

Numerical simulations were performed to evaluate relative effects of advection and diffusion of O_2 in spoil that could cause differences in the spatial distribution of Po_2 at mines 1 and mine 2. One simulation (Test 1) considered effects from both advection and diffusion, and a second test (Test 2) simulated effects from diffusion only, by setting the air permeability to zero. Both tests simulated conditions for 10 years since reclamation and used a generalized geometric configuration (Figure 4). For these tests, 15 cells within the interior of the spoil were simulated to contain 10 wt % pyrite (= 5.3 wt % sulfur), and surrounding cells did not contain any pyrite. This distribution of pyrite represents the selective placement of high-sulfur content overburden into compacted layers above the water table in the backfill. The geometry, initial conditions, and boundary conditions, which were held constant for the tests, are shown in Figure 4. The parameters specified are listed in Table 1.

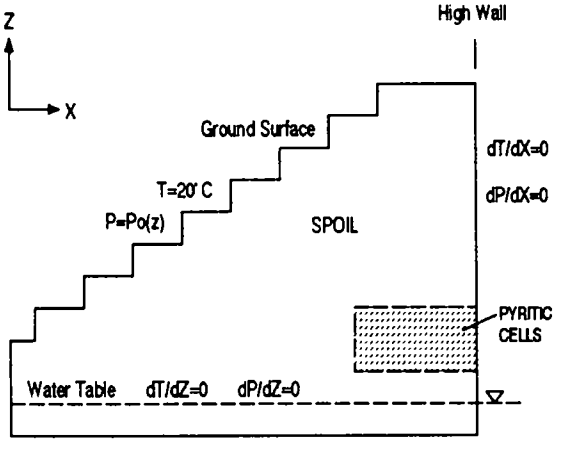

Figure 4. Boundary and initial conditions for numerical simulations. Shaded cells contain 10 wt % pyrite (= 5.3 wt % sulfur) initially; surrounding cells do not contain any pyrite.

For Test 1 where advection is the dominant transport mode, the fraction of pyrite oxidized after 10 years was much greater than that for Test 2 where diffusion is the dominant transport mode (Table 2). This difference in oxidation rate implies that temperature-driven air circulation (Figure 5), induced by pyrite oxidation, is significant and may exacerbate AMD formation because substantial O_2 is available for acid-forming oxidation reactions in mine spoil.

Thermal anomalies at depth as a result of pyrite oxidation are indicated by both simulated temperature profiles (Figure 6) and observed temperature profiles (Figure 2). Thermal anomalies in pyritic waste materials have also been reported (Bennett et al. 1989; Fielder 1989; Alpers and Nordstrom 1991). Higher temperatures are achieved in the more oxygenated environment, simulated by Test 1, because of greater pyrite oxidation and corresponding amounts of heat generation than for Test 2. Higher peak temperatures for simulations than for field observations are an artifact of concentrating pyritic material into one zone, rather than dispersing it throughout the spoil.

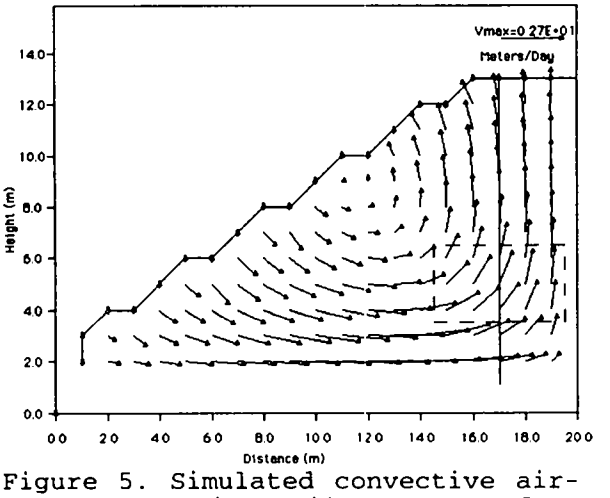

Figure 5. Simulated convective air-flow pattern in spoil 10 years after reclamation (Test 1). Vertical line marks the position of temperature and Po_2 profiles shown in Figures 6-9.

Table 1. Parameters used in numerical simulations.

Bulk density	1650 kg/m^3
Porosity	0.35
Infiltration rate	426.7 mm/yr
Thermal conductivity	2.0 W/m-K
Heat capacity	
Solid	760.0 J/kg-K
Water	4187.0 J/kg-K
Air	1000.0 J/kg-K
Air permeability	0 to 1×10^{-8} m^2
Tortuosity	0.6
Water content	15% by volume
Diffusion coefficient of oxygen in air	1.78×10^{-5} m^2/sec
Longitudinal dispersivity	10.0 m
Transverse dispersivity	1.0 m
Particle size	0.1 cm (radius)
Surface reaction constant	2.5×10^{-5} cm/sec
Diffusion coefficient in reacted zones	1.5×10^{-6} cm^2/sec

Table 2. Summary of Results of Test 1 and Test 2.

Test Number	Test 1	Test 2
Features	Dispersion-Advection	Diffusion Only
Tmax (°C)	27.814	23.006
P_{O_2} min (%)	17.79	4.10
Reacted Pyrite (%)	30.56	12.90

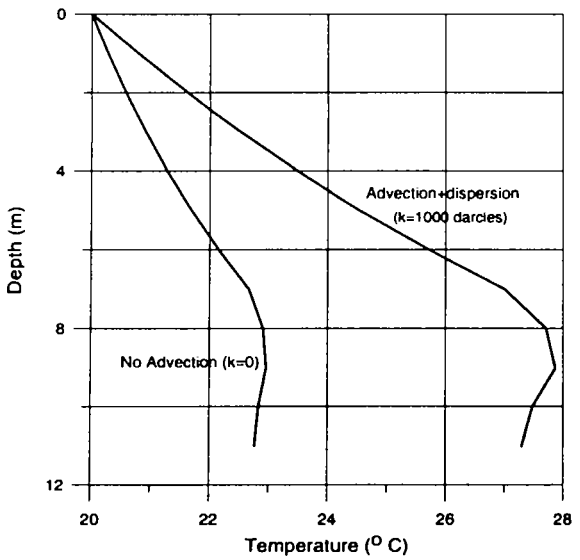

Figure 6. Simulated temperature profiles in unsaturated spoil 10 years after reclamation.

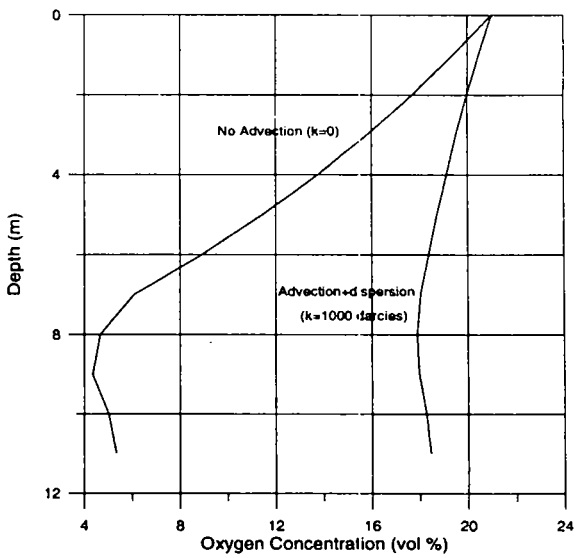

Figure 7. Simulated Po_2 profiles in unsaturated spoil 10 years after reclamation.

Uneven temperatures in mine spoil cause air convection in spoil (Figure 5). If the air flows from the land surface, where Po_2 is high, it brings O_2 into the subsurface. As air convection develops, a greater amount of O_2 is transported into mine spoil and greater rates of pyrite oxidation result, causing a perpetuation of the oxidation cycle. Consequently the temperature will be higher and convective flow is enhanced. However, the system is also controlled by the temperature, because once the temperature reaches about 55°C, bacterial catalysis slows or stops (Cathles 1979) and then the system reaches an equilibrium thermal condition and reaction rate.

Simulated Po_2 profiles for Tests 1 and 2 (Figure 7) are comparable with observed Po_2 profiles for mines 1 and 2, respectively (Figures 1 and 3). The simulated Po_2 profiles indicate that Po_2 remains relatively high throughout the spoil if advective transport takes place, but Po_2 decreases with depth if only diffusive transport takes place.

Results of Test 1 indicate that high Po_2 is attained in spoil when temperature-driven air flow is generated by the heat released from pyrite oxidation. In Test 2 for the simulation of only diffusive transport, Po_2 decreases exponentially from 21 vol % at the land surface to about 4 vol % at 9 m. Once the Po_2 declines to such a low level, the rates of acid-generating reactions are reduced. Results of laboratory experiments indicate the rate of pyrite oxidation reactions decreases when Po_2 is lower than vol 8% (Pugh et al. 1984) to as low as vol 1% (Hammack and Watzlaf 1990). This might be the situation observed in mine 2, where spoil is predominantly shale. The Po_2 remains low while most pore-water samples indicate negligible changes in concentrations of sulfate and iron with increasing depth below about 5 m (Cravotta et al. 1994b). Shale tends to disaggregate and become compacted, and hence shaly spoil (as in mine 2) has relatively low air permeability. In contrast, sandstone spoil (as in mine 1) tends to be very coarse and poorly compacted, which causes it to have higher air permeabilities. Neutralization by calcareous minerals may also contribute to the lower rate of AMD generation in deep spoil at mine 2 than that at mine 1.

If other conditions remain constant (Table 1), the air permeability of spoil is the determining factor for the occurrence of air convection.

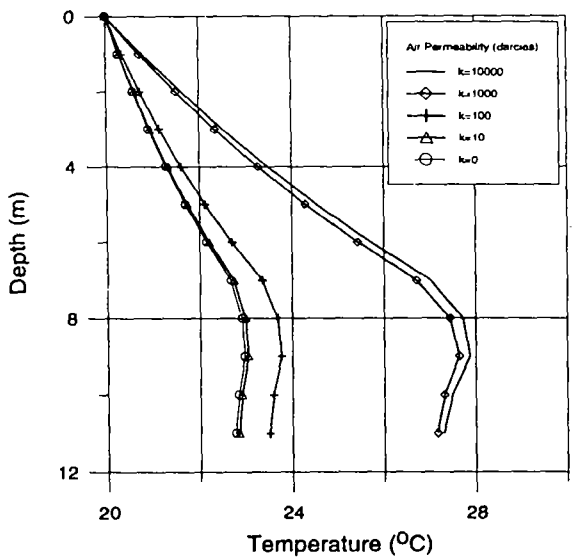

Figure 8. Simulated temperature profiles for different values of air permeability (k) 10 years after reclamation.

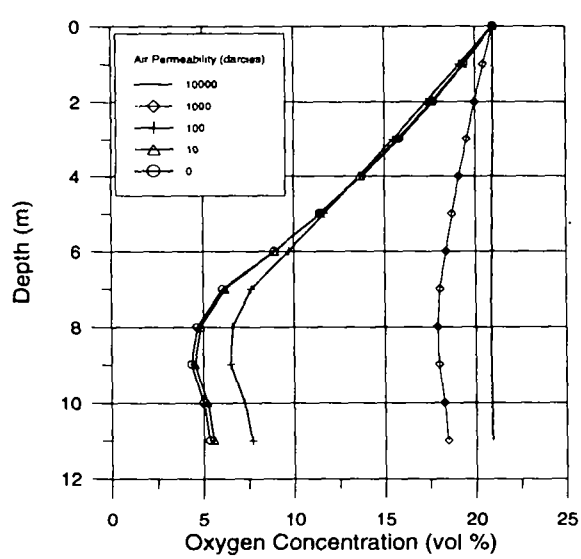

Figure 9. Simulated Po_2 profiles for different values of air permeability (k) 10 years after reclamation.

A series of numerical simulations was made in which only the air permeability was varied from 0 to 10^{-8} m^2. The temperature and Po_2 distributions predicted by these tests are shown in Figures 8 and 9, respectively. It is apparent that diffusion will be the dominant transport process when the air permeability is less than 10^{-10} m^2 (approximately 100 darcies), which is typical for soils. Pantelis and Ritchie (1992) also found that the oxidation rate in a heap with an air permeability of 10^{-10} m^2 is not much faster than that in which diffusion is the only gas transport process, but when the permeability is increased to 10^{-9} m^2, the oxidation rate is substantially faster.

Conclusions

Results of the numerical simulations indicate that differences in the distribution and transport of O_2 in coal-mine spoil can be explained by differences in the air permeability of spoil. Advective transport becomes significant if the air permeability of spoil is greater than 10^{-9} m^2, which is expected for blocky sandstone spoil. In the advective-dominant system, thermally-induced convective air flow, as a consequence of the exothermic oxidation of pyrite, supplies the O_2 to maintain high Po_2 within the deep unsaturated zone. Po_2 changes little with depth if advective transport of O_2 dominates, as at mine 1. In contrast, Po_2 decreases greatly with depth if diffusive transport of O_2 dominates, as in mine 2. Diffusive transport becomes significant if the air permeability of spoil is less than 10^{-10} m^2, which is expected for shaly spoil.

The numerical simulations, combined with field observations of the chemistry of pore-gas and pore-water samples, indicate that unsaturated-zone permeability is a critical variable affecting O_2 flux is spoil and the extent of pyrite oxidation. If the O_2 supply is not restricted, AMD formation can be severe. Thus, engineering practices to reduce O_2 transport into spoil may help to control the formation of AMD. Air permeability and O_2 supply in spoil can be reduced by covering the land surface with a low-permeability layer or by eliminating air-filled voids by compaction or filling with water. Field measurement of unsaturated-zone permeability, temperature, and pore-gas and water chemistry would be helpful for evaluation of the effectiveness of these practices.

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PUMPED CO-DISPOSAL OF BLACK COAL WASHERY WASTES IN AUSTRALIA[1]

by

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Abstract. The washing of black coal results in the production of coarse reject and tailings wastes, which historically have been disposed of separately. Loose-dumped coarse reject is highly porous, with largely air-filled voids. Tailings, disposed of as an aqueous slurry, have a high porosity with water-filled voids. By co-disposing coarse reject and tailings, the voids between the coarse reject particles can be filled with tailings. The mixture settles, drains, and gains strength and stiffness rapidly. It occupies less volume than the two waste products disposed of separately, potentially increasing the water return, and also facilitating rehabilitation. This paper briefly describes various co-disposal methods, detailing the behaviour, advantages, disadvantages, and cost implications of the co-disposal of coarse reject and tailings by combined pumping.

Additional Key Words: beaching, coarse reject, costs, tailings.

Introduction

Prior to mining and mineral processing, ore bodies comprise a heterogeneous mixture of different sized particles of different mineralogies. The mining and processing of the ore involves the separation of materials according to their particle size and mineralogy, and results in coarse and fine grained waste materials, which historically have been disposed of separately.

The washing of black coal to meet market specifications results in granular coarse reject (up to 100 mm [4 in] in size) and fine grained tailings (typically silt-sized). The coarse reject is conventionally loose-dumped, while the tailings are conventionally pumped as an aqueous slurry to a storage impoundment. The coarse reject disposed of alone has a high porosity (about 45 %), with largely air-filled voids. The tailings disposed of alone have an even higher porosity (about 55 % after they have settled), with water-filled voids. When coarse reject and tailings are co-disposed, the coarse reject tends to settle in loose contact, with tailings filling the voids between the coarse particles. Co-disposed washery wastes settle, drain, and gain strength and stiffness rapidly. They occupy less volume than the two waste products disposed of separately, potentially increase the water return, and can progressively and more readily be rehabilitated to a high level of future land use.

There are several methods of co-disposing of black coal washery wastes. This paper discusses these briefly, before concentrating on the method most often adopted in Australia, which involves the combined pumping of coarse

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reject and tailings. Beyond the coal mining industry, the co-disposal of overburden waste rock and tailings is being considered at a number of gold mines in Australia.

Methods of Co-Disposal of Coal Mine Washery Wastes

The co-disposal of coal mine washery wastes can be achieved by the following methods.

1. Co-disposal of dewatered tailings filter cake, produced by a belt press filter, and coarse reject is employed at many mines worldwide, including Mount Thorley in the Hunter Valley Coalfields of New South Wales, Australia. The dewatering of the tailings avoids the necessity to recover water after disposal, and facilitates the handling and rehabilitation of the combined wastes. However, the capital and operating costs are high (McKee 1992; in Williams 1992). The main operating costs are attributable to a high flocculant dose (up to 0.5 % by mass of dry tailings; up to 10 times that required for conventional thickening) and labor to maintain the operation of the belt press filters.
2. Combined pumping of a coarse reject/tailings mixture is employed at many coal mines worldwide (several in the USA, three in Queensland, one in New South Wales, and two in Indonesia), and is proposed at numerous existing and future mines. This method is described in detail later in the paper.
3. Pushing coarse reject into uncrusted, wet tailings has been successfully trialed at Ulan Coal Mines in New South Wales, Australia (Williams 1992). There is an optimum time after tailings disposal at which the coarse reject should be added to achieve good mixing. In the field, this optimum time is between one and two days. If the coarse reject is added immediately after tailings disposal, the coarse reject particles will reach the base of the storage before the tailings, and form a segregated layer. If the delay before the addition of coarse reject is too long, the tailings will have settled to the base of the storage, forming a segregated layer. If the tailings are allowed to settle and their surface allowed to desiccate and crust, the coarse reject will be supported by the tailings crust until sufficient coarse reject builds up to punch through it, resulting in bow-wave failure. Operationally, coarse reject must be added continuously, trailing behind the tailings discharge pipe as it is moved around the perimeter of the storage. A stable, trafficable deposit is formed as coarse reject emerges above the tailings surface. Operationally, this method requires a high management/labor input, to move the tailings discharge pipe and to ensure good mixing of the coarse reject. A stable/trafficable surface is possible only if there is sufficient coarse reject for it to rise above the tailings surface (a coarse reject to tailings ratio in excess of about 3 to 1 by dry mass).
4. Pouring tailings slurry over thin (about 0.3 m [1 ft] thick) layers of uncompacted coarse reject has been successfully trialed in South Africa (van Rooyen 1992). This method is effective in sealing coarse reject against possible spontaneous combustion, which is a feature of conventionally loose-dumped South African coarse reject. However, it requires a high management/labor input to place the coarse reject in thin layers and to move the tailings distribution pipes and is suited to only a narrow range of coarse reject to tailings ratios. It is unsuitable for coarse reject to tailings mass ratios of less than about 3 to 1.
5. The co-disposal of thickened tailings (using high-compression or paste thickening) and coarse reject

has been proposed. High-compression thickeners can achieve up to 65 % solids by mass and paste thickening can achieve 65 to 70 % solids, approaching that achieved by belt press filters. This should remove the need to recover water after disposal. The mixing of the thickened tailings and coarse reject could be facilitated by gravity, conveyor, pumping, or truck delivery of the thickened tailings. This method is yet to be trialed, but is being considered by a number of coal and gold mines. In the latter case, overburden waste rock would be co-disposed with thickened tailings.

Co-Disposal by Combined Pumping

Co-disposal by the combined pumping of a mixture of coarse reject and tailings is technically feasible from a pumping point of view, but operational refinements are required.

Pumping Characteristics

The conveyored coarse reject, conventionally thickened tailings (at about 30 % solids by mass), and make-up water are combined in a simple hopper. The wastes are then pumped by a high pressure (up to 3,000 kPa [435 psi]), large bore (approaching the internal diameter of the pipeline), centrifugal gravel pump at about 30 % solids, and at high velocity (2.5 to 4 m/s [8 to 13 ft/s]), to reduce the potential for the pipeline blocking. Pipeline blockages are usually readily cleared by increasing the line pressure. As a result of the relatively low solids concentration, a huge volume of water is required for pumped co-disposal, necessitating efficient water recovery. Particle sizes of up to 100 mm [4 in] (usually limited to about 50 mm [2 in]) can be pumped in a 200 mm [8 in] diameter pipeline, although the pipeline internal diameter should ideally be 4 or 5 times the maximum particle size. Pumping distances in Australia currently vary between 0.3 km [0.2 miles] and 2.5 km [1.6 miles]. Pumping distances greater than about 5 km [3 miles] may well make combined pumping uneconomic on the basis of pipeline capital and operating costs. Pumping heads currently range up to about 10 m [33 ft]. To maintain stable pumping conditions, some fines are required. Coarse reject to tailings mass ratios of between 1:1 and 6:1 have been successfully pumped. Pump and pipeline wear is high.

Beaching Behaviour

Co-disposed wastes beach at a slope of up to 1 (vertical) in 10 (horizontal), compared with a tailings only beach slope of about 1 in 100, and co-disposed wastes can be pushed up to slope angles approaching the angle of repose of the coarse reject material. On co-disposal, hydraulic sorting of the particles occurs, according to their particle size and specific gravity. These two effects may counteract, with the result that there may be little change in particle size down the co-disposal beach, with high specific gravity particles settling close to the discharge point and low specific gravity (coal-rich) particles settling at the far end of the co-disposal beach (Williams 1992).

Some wash out of fines (up to two-thirds of the tailings, the proportion increasing with decreasing particle size) is inevitable on pumped co-disposal. This results, in part, from the relatively low solids concentration and high velocity at which the washery wastes are pumped to limit the potential for pipeline blockages. Fines wash out increases with the inevitable gap-grading between the coarse reject and tailings, and with increasing plateness of the coarse particles. Crushing of the coarse reject, which would reduce the gap-grading and plateness of the particles, may be of benefit, provided that it does not substantially increase the proportion of fines in the mixture. For coarse reject to tailings ratios of less than 3:1, a mixture with a ratio

of about 3:1 will form on the co-disposal beach, with the residual fines washing out to form a tailings-like beach. To minimise the impact of fines wash out, co-disposal directed upslope is preferable to downslope co-disposal. Upslope co-disposal retards the flow of fines, allows them to be covered by later co-disposal, and avoids the construction of a major downstream containment. Water return of 75 to 90 % is possible, the percentage decreasing with increasing initial solids concentration.

The co-disposal mixture has a permeability (typically about 0.0001 m/s [0.0003 ft/s]; Williams and Kuganathan 1993) mid-way between that of coarse reject only and tailings only, at about 1,000 times that of the silt-sized tailings alone. Drainage paths exist around the coarse reject particles in loose contact, against which the angular tailings particles form a loose packing. The flow on the co-disposal beach is about 100 mm [4 in] deep, making the surface almost immediately trafficable. The co-disposed mixture rapidly achieves a dry density of up to 1.5 tonne/cubic m [94 lb/cubic ft], at a gravimetric moisture content as low as 15 % and a porosity as low as 30 %. The overall physical characteristics of coarse reject disposed alone, tailings disposed alone, and co-disposed wastes are compared in Table 1.

Table 1: Overall dry density, moisture content and porosity of coarse reject only, tailings only, and co-disposed wastes.

MATERIAL	DRY DENSITY (t/m^3) [pcf]	MOISTURE CONTENT (%)	POROSITY (%)
Coarse reject only	1.2 [75]	5-10	45
Tailings only	0.8 [50]	70	55
Co-disposed	1.5 [94]	35-40	35-40

Relative Ease of Pumped Co-Disposal

The relative ease of pumped co-disposal depends on the following parameters.

1. Coarse reject to tailings mass ratio: Generally, the higher the ratio the better, since it reduces the total fines wash-out and results in a steeper co-disposal beach.
2. Particle size distribution of mixture: There is, inevitably, little overlap between the coarse reject and tailings sizes. The more pronounced the gap, the less efficient is the trapping of fines.
3. Coarse reject particle shape: Rounded particles are more readily transported and pack and trap fines better than platey particles, but give a flatter beach slope.
4. % solids: Provided pipeline blockages are avoided, the higher the solids concentration the better. This results in a steeper beach slope and a reduced volume of water in circulation.
5. Flow velocity: Provided pipeline blockages are avoided, the lower the flow velocity the better. This results in a reduced wash out of fines.
6. Geometry of deposition: A steep initial beach slope results from burial of the discharge, until a blow-out occurs.
7. Level of decant pond: This affects water clarity and discharge into water will slow the segregated fines.
8. Direction of discharge: Upslope pumped co-disposal is far preferable to downslope, preventing the segregated fines from running and allowing them to be progressively covered. However, it requires more management/labor input.

Potential Problems with Pumped Co-Disposal

The potential problems with pumped co-disposal include the following.

1. Excessive pump wear: This can be largely overcome by using a larger pump bore, several times the size of the largest particle and similar to that of the pipe.
2. Excessive pipe wear: Pipe wear will be highest where the line pressure is greatest (near the pump). High density polyethylene (HDPE) and mild steel pipes wear excessively, but may be appropriate for short pumping distances (< 0.5 km [0.3 miles]). Ceramic- and polyurethane-lined pipes perform well, at a higher capital cost, while the more brittle basalt-lined pipes perform less well. A 10 mm thick lining may be optimal.
3. Pipeline blockages: High pressure (3,000 kPa [435 psi]) pumps largely overcome pipeline blockages.
4. Long pumping distances: As a rule-of-thumb, an additional pump should be added (preferably along the line, although this necessitates remote power) for every km length of pipeline.
5. Variable coarse reject/tailings feed: High pressure pumps provide a robust system, capable of handling variations in the coarse reject/tailings feed.
6. Moving discharge point(s): Moving the discharge point or points is recommended to minimise rehandling of the mixture and for better control. It can be done by dragging the pipeline or, preferably, by using a number of discharges in rotation and adding lengths of pipe as required. The optimum number of discharges is dependent on the storage geometry.
7. Water recovery and recirculation: Efficient water recovery for recirculation is vital, requiring substantial management/labour input. The clarity of the return water is relatively unimportant.

Co-Disposal Storages

New mines will likely co-dispose above-ground, either upslope or into paddocks, while existing mines may have dis-used ramps or pits available. Upslope co-disposal above-ground offers the potential to store up to five times the volume of washery wastes stored by downslope co-disposal, for the same height of downstream containment. Co-disposal offers a more efficient use of available in-pit storage volume than the separate disposal of coarse reject and tailings. Co-disposal into ramps should preferably be upslope, to maximise the available storage volume, reduce the impact of fines segregation, and increase the stability of the embankment separating the ramp from the pit.

Water Recovery from Pumped Co-Disposal

Co-disposal by combined pumping requires the recovery and circulation of large volumes of water. It is therefore vital that water recovery be efficient. Water clarity is less important, since the water will be recirculated with the co-disposed wastes. Various methods have been or can be used to recover and recirculate water from the co-disposed wastes. For in-pit and downslope co-disposal, pumping from a conventional decant pond is appropriate. For upslope co-disposal, underdrainage is required in addition to pumping from an upslope decant pond.

Costs of Pumped Co-Disposal

The costs of pumped co-disposal are offset by the elimination of tailings dams and coarse reject dumps. Jeebropilly Colliery, in the Ipswich Coalfields of south eastern Queensland, Australia, operates pumped co-disposal for about 15 % of the cost of the previous separate disposal of tailings to a dis-used pit and coarse reject to a dump. However, Jeebropilly has dis-used pits available for co-disposal, and experienced difficulties with the dumping of their highly degradable, clay-rich coarse reject. As a guide, pumped co-disposal should cost of the order of half the cost of conventional separate disposal, depending on a range

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of site specific and other factors. For both new and existing mines, the costs of pumped co-disposal must be weighed against the costs of conventional separate disposal.

Cost items associated with conventional coarse reject dumps include the following.

- Coarse reject hopper.
- Truck capital, operating, maintenance, and replacement costs.
- Land cost.
- Construction and maintenance of haul roads.
- Collection of seepage from the dump, and treatment if necessary.
- Rehabilitation costs. To reshape and cover a coarse reject dump costs up to $A 75,000/ha [$US 22,500/acre], but the costs can be greatly reduced by progressive reshaping and rehabilitation.

Cost items associated with conventional tailings dams include the following.

- Thickener capital, operating, and maintenance costs.
- Tailings dam construction and raising.
- Land cost.
- Capital, operating, and maintenance costs of pumps and pipeline(s).
- Water recovery and return.
- Rehabilitation costs. To cover crusted tailings costs in the range from $A 40,000 to $A 80,000/ha [$US 12,000 to $US 24,000/acre].
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Cost items associated with pumped co-disposal include the following.

- Tailings thickener capital, operating, and maintenance costs. Where pumped co-disposal has been adopted, a conventional tailings thickener has been retained. There is scope for some of the tailings to by-pass the thickener, avoiding the need to add make-up water, with consequent cost savings.
- Construction of a hopper for combining the coarse reject, thickened tailings, and any make-up water. This can be a modest, low-cost facility.
- Land cost. This will be less than that required for the separate disposal of coarse reject and tailings, because of the reduced storage volume occupied by co-disposal.
- Capital, operating, and maintenance costs of pumps and pipeline(s). These will be substantially higher than the corresponding costs for tailings only, and may be the largest cost item. A low-cost pipeline may be adopted for emergency purposes. Instrumentation should be installed to warn of possible pipeline blockages.
- Operating costs associated with moving the co-disposal discharge.
- Costs of recovery and recirculation of water, preferably involving a separate water storage dam.
- Operating costs associated with re-shaping the co-disposal deposit.
- Rehabilitation costs. These will be far lower than those for separate coarse reject dumps and tailings dams. A nominal cover after progressive re-shaping may be all that is required.

For existing mines, a number of situations offer opportunities to switch from conventional separate disposal to pumped co-disposal. These include an exhausted coarse reject dump and/or tailings dam, coarse reject haul truck(s) requiring replacement, and expansion of the mine, and mining voids becoming available. For new mines, pumped co-disposal can take advantage of not being locked into existing plant and methods, a comprehensive cost-benefit analysis, flexibility in the siting of waste handling plant and waste storages, and rehabilitation requirements.

Rehabilitation of Pumped Co-Disposal

Pumped co-disposal offers the potential for progressive, ready rehabilitation to a high level of future use. The co-disposal discharge

should be shifted to build up the desired final land form, by regularly moving a single discharge, or using a number of discharges in rotation, extending out over the deposit as it builds up. Upslope co-disposal lends itself to progressive rehabilitation, since it minimises the impact of fines segregation, maximises the use of hydraulic placement, and allows the downstream slope to be built up, using co-disposed material, to the desired final slope angle.

Concluding Comments

There are several different approaches for the disposal of black coal mine washery wastes. The pumped co-disposal of the combined coarse reject and tailings is an economical alternative to the conventional separate disposal of the two waste products, which has been adopted at many coal mines worldwide and is being considered at numerous other mines. It will find application at existing and new mines where its potential benefits are recognised and can be realised. Pumped co-disposal has a number of problems including pipe wear and the segregation of fines on the beach. However, an appreciation of these problems in the design and operation of pumped co-disposal will minimise their impacts.

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SITE CHARACTERIZATION AND CONTAINMENT/REMEDIATION OF ACID MINE DRAINAGE AT AN ABANDONED MINE WASTE DUMP

by

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Abstract. This paper focuses on the preliminary results of laboratory tests to evaluate a new suspension grout consisting of a mixture of a naturally occurring lignite coal based wax "montan wax", sodium bentonite "pure gold grout", and water. The test program assesses the suitability of the grout for creating subsurface containment barriers in coal waste dump sites for acid mine seepage control to surface and ground waters. The laboratory activities evaluated the reduction in permeability that could be achieved in a coal waste dump site under optimum conditions and the compatibility of the grout with representative waste from the test site. Information on geological, geochemical and geophysical about the test site is presented. Laboratory formulation of the grout is complete and simulation of field condition is in progress. Pregrout geophysical surveys for determination of hydrogeologic conditions at the site are also completed. Based on geophysical surveys, a grout curtain is proposed which will consist of two rows of grout placement holes in an array across the seepage area toward Belt Creek in Montana. Post-grout geophysical survey will be carried out immediately after grouting work. Performance of the grout curtain will be monitored by collection of water samples from monitoring wells in the Belt Creek and seepage area.

Additional Key Words: grouting, sealing, barriers, seepage control, grout formulation, montan wax, bentonite, permeability, compatibility tests, coal waste dump site, ground water contamination, geophysical, geochemical, etc.

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Introduction

Acid mine drainage (AMD) from past mining practices is a major source of contamination of rivers, streams, and aquifers throughout the United States. The migration of surface and groundwater through active and abandoned mine workings and tailing piles, combined with bacterial oxidation of sulfides, is the major cause of the formation of AMD. In the eastern United States, there are thousands of abandoned surface and underground, high-sulfur, coal mines. As a result, AMD is a significant source of pollution of surface and ground water. However, in the western United States, AMD is primarily the result of hard-rock mining. For example, the state of Colorado has over 20,000 abandoned mines, some of which are sources of contamination of rivers and streams.

Montan Wax is essentially a mixture of waxy constituents consisting of monohydric alchohol esters and high-molecular-weight acids with some resinous and asphaltic material.

The idea of using Montan wax to construct containment barriers began because of serious environmental problems in Bitterfeld, Germany. MIBRAG is a large industrial company with headquarters in Bitterfeld that developed the montan wax grout. MIBRAG was responsible for lignite coal mining operations in the area. Montan wax deposits are present in these coal fields.

In the Bitterfeld area, there are several industrial waste disposal pits where leachates are entering the local aquifer, contaminating the drinking-water supply. (Voss, et. al., 1994). MIBRAG researchers began testing the feasibility of constructing containment barriers with montan wax grouts in several field demonstration projects at the disposal sites. The sites contained unconsolidated soils with relatively high rates of hydraulic conductivity (e.g., 10^{-3} cm/s). After permeating the soils with a mixture of montan wax, water, and bentonite, the conductivity of the soil was reduced by as much as five orders of magnitude (Caldonazzi, et. al., 1993).

Based on the positive results of the field demonstration projects in Germany, the U.S. Department of Energy's (DOE) Office of Technology Development (OTD) is evaluating the montan-wax emulsion as a containment material for remediating contaminated DOE sites. Hydraulic conductivity tests have been conducted on soil specimens from the Hanford and Sandia sites. Laboratory studies, namely hydraulic conductivity, penetration rate, waterproofing characteristics, chemical compatibility, and durability have shown that these soils are groutable with montan wax emulsions. After permeating the soils with straight montan wax (no added bentonite), the hydraulic conductivity of soil has been reduced by as much as five orders of magnitude. (Voss, et al., 1993)

Chemistry of Montan Wax

Montan wax is found in lignite which is not far advanced into the carbonization process. The resistant fossil plant leaf wax has remained uncoalified as a result. It is thought that montan wax results from fossil palms similar to modern carnauba wax palms. Montan wax is recovered by pulverizing the lignite and placing it in a solvent extractor for removal of the plant wax. Montan wax is a complicated mixture of primarily wax, resin, and asphaltene - like substances. The typical dark color of the base montan wax is due to the small percentage of asphaltene - like substances. Montan wax has a distribution of C24 - C32 carbon chain esters of long-chained acids and long-chained alcohols. Hydrocarbons, free alcohols, and ketones exist only in small quantities.

Because the wax is extracted from the mining of lignite, it is classified as a mineral wax. But, it is a fossil plant wax, not a petroleum wax, and the properties are comparable to natural plant waxes. The asphaltene-like material contained in the wax is so named because it is black; it does not have the same chemistry as asphalt.

Montan waxes are used for their hydrophobic and lubricating properties as well as their hardness and high melting point. Montan wax has a natural acid number and a long chain hydrophobic molecule with a short hydrophilic section. For water-proofing of aggregates, the hydrophilic section wets the aggregates and the hydrophobic section provides the water repellency. This property is not found in paraffin waxes.

Montan wax grout in comparison to conventional cement grouts offers superior sealing characteristics because ground water does not wash it out and pore cavities are sealed by wax deposition. If large pore sizes exist in the rock mass, bentonite is added to the wax to improve sealing performance. Montan wax is not brittle and has non-desiccant characteristics. It is environmentally safe and chemically and micro-biologically stable. (Karabon, 1978)

General Characteristics and Uses of Montan Waxes

Montan wax is composed of hard, friable, lustrous materials ranging in color from black to amber. The natural ester wax is derived from fossilized plants and is a complex mixture of components. Montan wax products in the United States are named ALPCO by the producer of crude montan wax. ALPCO produces several waxes. ALPCO 16, 1600, and 1650 are suitable for environmental applications. For formulations of montan wax and bentonite, only ALPCO 16 is being used. ALPCO 16 is a black, hard and lustrous wax. Its moderate acid number makes it easily saponified and suitable for emulsions for mold releases, polishes, water-proofing applications, asphalt emulsions, cable dressing, lubricants and grease. ALPCO 16 is a modifier for asphalts, temporary soft coatings,

sealants, and undercoating materials.

ALPCO 16 has a specific gravity of 1.01 at 25 C°, bulk density from $4.9x10^2$ to $5.3x10^2$ kilograms per cubic meter, melting point from 81 to 85 C°, and flash point of 345 C°. All ALPCO waxes are resistant to oxidation but will biodegrade. All ALPCO waxes are non zardous by U.S. Department of Transportation regulations.

Potential Benefits of Montan Wax Grout as a Sealing Material

When injected into the fractured rock mass, montan wax emulsions containing polymer silicate creates an elastic block which firmly bonds with the pore walls. The sealing characteristics of montan wax grout can be adjusted for mobility, precipitation, and configured for the individual geological conditions. An example of this type of application is sealing of the drill hole walls by introducing montan wax emulsion into the drilling fluid containing polymer silicate. As a result, the introduction of heavy metals into the drill hole while drilling is stopped. Montan wax emulsion, containing bentonite, and containing large pore openings is also used for soil stabilization. This application improves water isolation properties of the soil mass even in high permeability environments.

The properly designed montan wax grouts are insoluble in ground water, neutral, and biologically nondegradable in the saturated fractured rock mass environment. The montan wax does not stratify during hardening nor stabilize during injection and it has excellent flow-ability characteristics. It develops strength quickly after injection and it is used for soil stabilization of hazardous waste sites in the Lausitz region, Bad Erna, Germany. Sealing characteristics of montan wax placed within fractures for isolating ground waters in the central German mining area of Lochau and Meserburg - OST have been documented, (Voss, et al., 1993).

The montan wax grouting technique is used for encapsulation of contamination sources or to prepare it for a subsequent restoration purpose. For control of contaminant migration in lateral, horizontal and inclined directions, injection of montan wax is practiced in the brown coal fields of the former East Germany.

General Characteristics of Pure Gold Grout (Bentonite Clay Grout)

Pure Gold Grout (PGG) is a specifically formulated, high solids, sodium bentonite grout. PGG is an easy mixing, single component, organic free bentonite clay grout. It was engineered to form a contaminant resistant seal without affecting ground water chemistry. PGG is a technically superior replacement for traditional cement grouts. It will form a low permeability and a flexible clay seal which impedes interaquifer fluid movement and infiltration of surface contaminants into the borehole.

PGG is commonly used in sealing boreholes or the annular space of monitoring wells to control contaminant infiltration and preserve ambient groundwater quality. PGG's pH ranges from 5 to 6-standard units. PGG is contaminant free and chemically stable. PGG has a low permeability with test results ranging from $1x10^{-7}$ to $1x10^{-9}$ cm/s against permeants ranging from a pH of 2 to 12. PGG has a low formation loss, and minimum flow through highly permeable soils. It remains flexible, maintains putty-like consistency over time and will re-hydrate. PGG is mixed with a grout mixer and trimmed with a positive displacement pump. It can be mixed in a slurry up to 30% solids, remains placeable for up to two hours, and sets in eight hours. PGG is manufactured by American Colloid Company. (CETCO, 1994).

Site Characterization

Site characterization for planning the grout test involved drilling, coring and mapping, the installation of monitoring wells, the collection of geochemical data from the monitoring wells, diversion ditching and performing geophysical surveys.

Site Survey

The field site selected for this study is the Anaconda Coal Mine's reclaimed coal processing waste dump near Belt, MT. AMD is a major source of contamination of Belt Creek and the unconfined aquifers at the site. The mine was an active underground coal mine from the 1890s to the 1920s, and at one time, was the largest coal mine in Montana, with daily production of 2,500 tons. The mined coal was transferred about 914 m from the adit to a coal processing plant. Washed coal was coked and coal waste dumped on the banks of Belt Creek. In the 1980s, $6.5x10^5 m^2$ of the site was reclaimed by the Abandoned Mine Reclamation Bureau, Department of State Lands, State of Montana.

The 8,100 m^2 testing site is bounded by Belt Creek, an all-weather road, and a diversion ditch which discharges flow of about 378 lpm from the mine adit into Belt Creek. AMD from the diversion ditch flows through the mine waste dump and seeps to Belt Creek. Aquatic life has disappeared up to 8 kilometers down the creek. The site is presently used by the Department of Transportation, State of Montana to store railroad ties and gravel for making asphalt. The site is leveled, and a foot of top soil covers the area.

Drilling

Six hydrologic monitoring wells (MW) have been drilled using a hollow stem auger drill (Figure 1). The wells were all drilled to bed-rock and range from 4.2 to 7.2 m (Table 1). During drilling, subsurface materials were characterized by examining materials coming up the outside of the auger flights. Split spoon sampling was not conducted during drilling. Materials encountered were in no way uniform throughout the site and ranged from gravel to clay to

coal to a reddish "muddy" material which may have been decomposed, liquified scoria and mine waste. Drilling at every location except MW-4 was stopped when augers began scraping on a compact solid surface at depth. It was postulated that this solid surface may be cemented gravel underlying the coal wastes. The cemented gravel could be caused by precipitation of minerals due to pH changes in the water migrating through the coal wastes into native materials. A surface exposure of cemented gravel is located adjacent to Belt Creek a short distance upstream from the diversion ditch discharge point. At MW-4 gravel, clay and silt were encountered at depth rather than the "cemented gravel". Once the drilling was complete, groundwater monitoring wells were installed with 10 cm diameter 40 PVC pipe. Three meter screened sections were used in each well to intercept the groundwater table. Screened sections were filter packed with sand. Above the sand, bentonite chips were used to fill the remaining annular space. A flushmount with concrete seal was then installed at the surface. After installation activities, the wells were developed by blowing water and sediment from the well using pressurized air from the drill rig and then surging and bailing with a disposable bailer to purge the wells of fine material (Tetra Tech, Inc., 1995). This work was sponsored by the Department of Environmental Quality, Reclamation Division, State of Montana. Drilling of monitoring wells was contracted to Boland Drilling, Great Falls, MT., and hole logging was done by the Tetra Tech, Inc. Helena, MT.

Geochemical Data

Water samples collected from monitoring wells were analyzed and scanned for their metal contents. Conductivity ranged from 8,200 (MW-4) to 26,000 (MW-3) micro mhos/cm and pH ranged from 1.9 (MW-3) to 4.0 (MW-4). At about 6 meters from MW-2 (Figure 1) on the bank of Belt Creek, decolorization and bubbling of water was in progress and a water sample was collected from this location. Conductivity and pH measured for this location were 566 micromohs/cm and 4.7 respectively. An additional water sample was taken from surface diversion ditch and it had conductivity and pH of 2,800 micromohs/cm and 2.4 respectively. Water samples taken from Belt Creek, upstream from the test site have conductivity and pH content of 415 micromohs/cm and 7.4 respectively. Water analysis for the contaminated samples show that pH was quite low and dissolved solids moderately high. The dissolved solids are largely composed of sulfates. Iron, magnesium and calcium are the most common cations detected, but there are probably other cations present that were not tested for. The main concern is the low pH but there were small amounts of toxic metals, mainly lead and zinc. Lead and zinc metal ions were detected in all of monitoring wells above limits for drinking water established by Environmental Protection Agency in mg/l.

Compatibility Test Results

Chemical compatibility testing was conducted in order to provide a preliminary indication of the performance of the grout when exposed to a variety of metals that are representative of typical AMD constituents present at the coal waste dump test site. The analysis of water samples is not complete enough to simulate exactly the potential effects on the grout; however, the simulated solution's pH is 2, which will be a tougher test for the grout, but the total dissolved solids will have about 2,000 ppm, which would make an easier test for the grout.

Grout Cost Comparison

Cost estimation for grouting projects is an art and much depends on site-specific conditions, materials availability, grouting contractors mobility and experience. However, the cost data, presented in Table 2, are for material cost comparisons purpose for the various grouts. These costs include the cost of material and shipment to Denver only, and exclude labor cost for preparation of grouts.

Portland Cement Type II grout is the cheapest one but it has its own limitations for environmental applications. The second cheapest grout is montan wax and bentonite clay-based (Pure Gold Grout) materials with unique properties. These materials may have a wide application in the environmental field for containment and stabilization of abandoned coal, uranium and hard-rock mines. The most expensive grouting materials are microfine cement and sodium silicate. These materials are routinely and successfully used at civil engineering projects, however, economically they would have limited application in large volume mining operations for AMD control.

Laboratory Formulation

American Colloid Company has been active in formulation of montan wax and bentonite grout for acid mine seepage control at the test site. The first phase of this effort focused on formulation of grout in the laboratory; and the second phase of this effort will consist of field injection of the formulated grout in the Anaconda Coal Mine waste dump site near Belt, MT., where performance of injected grout will be determined by post-grout geophysical surveys and hydrologic monitoring.

Laboratory formulation of montan wax and bentonite grout is complete. A total of nineteen formulated samples of montan wax and bentonite (Pure Gold Grout) were prepared in the laboratory and all of these samples were subjected to standard cone penetration testings. Pure Gold Grout (PGG) is the type of bentonite grout used for laboratory testing. PGG is used as the standard basis for core penetration testing of all formulated samples. Two formulated samples out of nineteen were closely comparable to PGG's cone penetration results. The results of these two formulated samples are presented in Table 3.

The two formulated samples are composed of 1) 1% montan wax, 30% PGG, and 69% deionized water, 2) 5% montan wax, 25% PGG, and 70% deionized water. Permeability studies resulted in the measurement of hydraulic conductivity of 2.04×10^{-8} cm/s after 142 days for 1% Montan wax mixture.

The permeability measured for 5% Montan wax was 1.12×10^{-7} cm/s after two weeks. For both grout formulations, falling head permeability tests were used and the permeant had a pH of 2. Furthermore, 1% montan wax, PGG 30%, and 69% deionized water formulated grout was mixed with augered coal waste dump samples from the testing site at a ratio of 1:1. This mixture is permeated with tap water in the laboratory. The average hydraulic conductivity measured after 56 days was 2.71×10^{-8} cm/s. This test is still in progress. This is considerably less than the level of 10^{-6} cm/s specified by EPA for use in liner systems. Nevertheless, the reduction in permeability afforded by the montan wax based grout is significant and it may be a useful barrier material for applications where the containment time is limited, or where a lower degree of containment can be tolerated.

Geophysical Surveys

AMD from the sealed adit of the abandoned Anaconda coal mine is directed east through a drainage pipe downslope to a diversion ditch which brings AMD from other mines upstream. Flow is then directed northeasterly and discharges into Belt Creek, which flows in a northwesterly direction at this location. The diversion ditch is constructed on top of wastes from coal processing and angles toward Belt Creek where it discharges over a riprap embankment to prevent erosion. Consequently, a positive hydraulic gradient is established along the ditch which is approximately normal to the topographic gradient of the old surface drainage.

The seepage of AMD that has been observed in Belt Creek, upstream from the discharge point of the diversion ditch, thus could be due to leakage from the ditch, or the near surface groundwater moving through the waste materials, or a combination of both. Geophysical surveys were performed on the site to characterize the hydrology and attempt to delineate the primary source of the AMD seep into the creek.

Electromagnetic (EM34) surveys were performed to map the subsurface conductivity of the site, and self-potential (SP) surveys were made to determine direction of significant ground water movement in the area. Additionally, a ground-penetrating radar method was evaluated as a potential characterization technique. The EM34 data were taken using the 10m coil spacing in the horizontal and vertical dipole configurations to investigate both the fill material, which varied in thickness from about 3m to 8m, and the buried geologic formation beneath the fill. The horizontal dipole configuration has a depth of investigation up to approximately 7.5m, whereas the

vertical dipole configuration responds to conductive layers up to 15m depths.

Geophysical surveys were made in August and again in October, 1995. Surface conditions at the site were significantly different between the two dates. These conditions affected the SP surveys with excessive noise because of the electrode coupling problems. Also, the surface of the site has been capped, revegetated, and used by the County for storage of gravel and asphalt for road construction, compounding the coupling problem. EM34 surveys, however were highly repeatable, indicating little change in subsurface groundwater conditions between the two survey dates.

Figures 2, 3, and 4 illustrate the horizontal dipole, vertical dipole, and SP data, respectively, from the later surveys in October, 1995. Included on the maps are the survey line data points (small circles), sample well locations, and the approximate boundary of the property (heavy solid line). The boundary line is a barbed wire fence which affects the response of the EM34, and data near this boundary is not diagnostic; however, in the central portion of the site on the horizontal dipole data map (Figure 2), a high conductivity ridge originating at the diversion ditch between 50-60m, and oriented toward the approximate location of the seep into Belt Creek, is apparent. The vertical dipole data (Figure 3), which is responding proportionately greater to deeper ground conductivity, does not show a prominent high anomaly at this location, and the SP map (Figure 4) is also relatively non-descript.

Interpretation of these geophysical surveys indicates potential leakage from the central portion of the diversion ditch, accumulation and very slow percolation of the already acidic water through the coal processing wastes just above the bedrock surface (which is an impermeable cemented conglomerate), dissolution of metals in the wastes, and seepage below the water level at the bank of Belt Creek. The self potential data is non-diagnostic because the rate of flow and hydraulic gradient (pressure) is minimal, generating no streaming current. Horizontal dipole survey data indicate the primary water movement is at or above the bedrock layer, and the vertical dipole data indicates little likelihood of communication with any deeper groundwater regime.

The conclusion from the interpretation of the geophysical surveys is that the objective of the project, i.e., evaluating the effectiveness of a montan wax bentonite grout curtain (Figure 5), can be achieved by configuring the placement holes in an array across the channel of acid mine drainage and monitoring the effect on the location and rate of seepage into Belt Creek.

Summary

The laboratory results of the preliminary evaluation of montan wax and bentonite (Pure Gold Grout) for constructing

containment barriers at an unconsolidated coal waste dump site for seepage control is promising. Permeability testing for a formulated 1% montan wax, 30% PGG, and 69% dionized water had average hydraulic conductivity of 2.04×10^{-8} cm/s after 142 days. The permeant had pH of 2. This formulated grout is mixed with an augered coal waste dump sample in the laboratory at a ratio of 1:1. This mixture was permeated with tap water. The average hydraulic conductivity measured was 2.71×10^{-8} cm/s after 56 days. This test will be repeated soon and permeance will be replaced with an acid solution of pH2. Laboratory measured hydraulic conductivities exceed the maximum level of 10^{-6} cm/s specified by EPA for use in liner systems. Geophysical surveys were performed at the site to characterize the hydrology in an attempt to delineate the primary source of the AMD seep into the creek. Interpretation of these geophysical surveys indicates potential leakage from the central portion of the diversion ditch, accumulation and very slow percolation of the acidic water through the coal waste dump just above the bed rock surface, dissolution of metals in the wastes, and seepage below the water level at the bank of Belt Creek.

In summary, the interpretation of geophysical surveys have resulted in configuring the grout placement holes in an array across the acid mine drainage channel. Grouting work will be completed soon and a post-grout geophysical survey will be carried out for determination of grout effectiveness. Finally, performance of grouting work will be monitored by collecting water samples from wells and by monitoring the rate of seepage into Belt Creek.

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TABLE 1. LABORATORY FORMULATION RESULTS FOR MONTAN WAX(MW) AND PURE GOLD GROUT(PPG)

Grout Type	PGG gram	MW ml	Deionized water ml	Cone Penetration** 15 min mm	24 hr mm	Hydraulic Conductivity cm/s
PGG Grout Standard	300		700	>100	24	1.0×10^{-7} - 1.0×10^{-6}
MW/PGG 1	300	10	690	>100	22	2.04×10^{-8} after 142 days*
MW/PGG 2	250	50	700	>100	36	1.12×10^{-8} after 14 days*

*Simulated site water sample had a pH 2.0 Falling Head Permeability Test were based on Rigid Wall Method (ASTM: D2434-68)
**Standard Test Method for Cone Penetration of Lubricating Grease (ASTM: D217-86)

TABLE 2. GROUT COST ESTIMATE*

Grout Type	$/m³
Montan Wax (MW) and Pure Gold Grout (PGG)**	
1: 1% MW, 30% PGG, 69% Deionized Water	120
2: 5% MW, 25% PGG, 70% Deionized Water	90
Portland Cement Grout Type II, mixed at ratio of 1 to 1	70
Microfine Cement, mixed at ratio of 1 to 1	1,170
Sodium Silicate	1,250

*These cost estimates include cost of material and shipment to Denver and excludes labor costs for preparation of grouts.
**Pure Gold Grout is a registered trade mark of the American Colloid Company.

TABLE 3. MONITORING WELL DATA FROM ANACONDA MINE RECLAIMED WASTE DUMP, BELT, MONTANA

Monitoring Well	pH	Conductivity micromhos/Cm	Temperature C°	Well Depth m	Well Evaluation m	Depth to Water m	Water Evaluation m	Depth of Water m
MW - 1	3.9	9,000	11.8	4.2	30.3	3.7	26.6	0.48
MW - 2	3.4	14,500	10.7	4.8	29.8	3.2	26.7	1.64
MW - 3	1.9	26,000	12.2	4.4	30.6	3.5	27.0	0.79
MW - 4	4.0	8,200	10.6	7.2	31.4	3.4	27.0	2.84
MW - 5	2.4	8,900	10.1	5.2	31.9	4.8	27.0	0.06
MW - 6	3.8	12,000	10.3	5.4	32.3	4.6	27.6	0.70

This information was collected from testing site on August 09, 1995

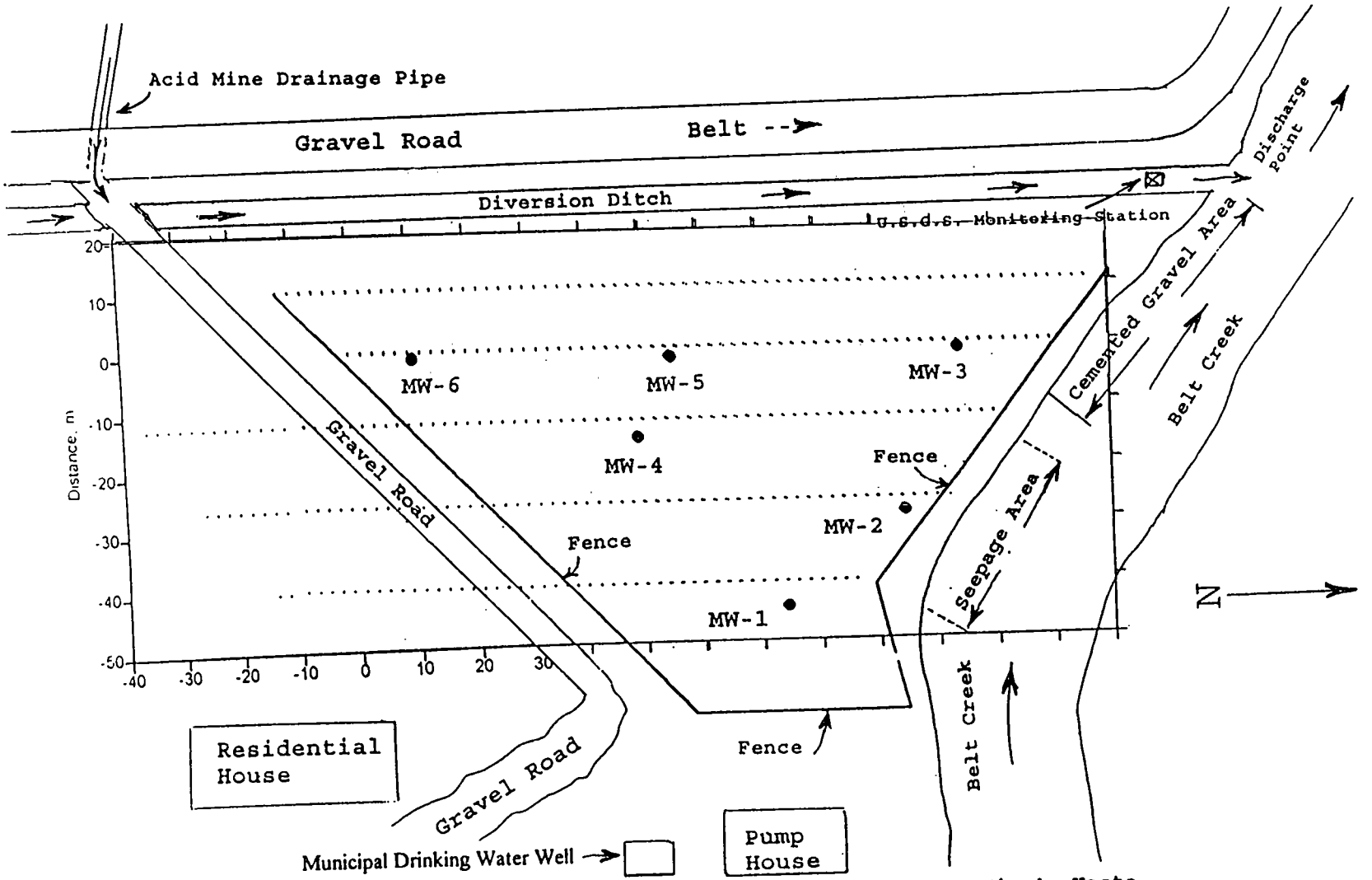

Figure 1. Monitoring Well Locations at Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

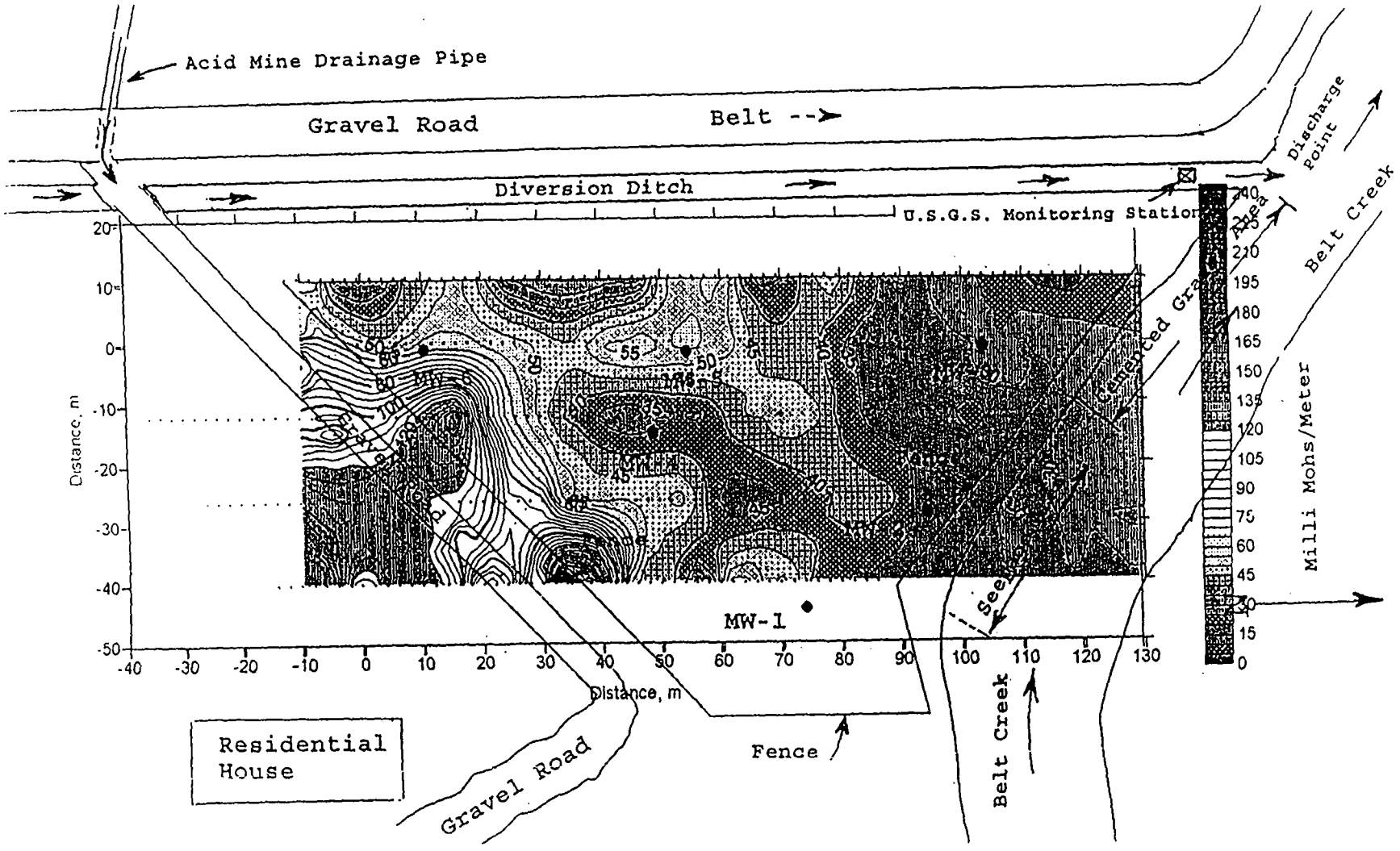

Figure 2. Geophysical Survey, EM34, Horizotal Dipole, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

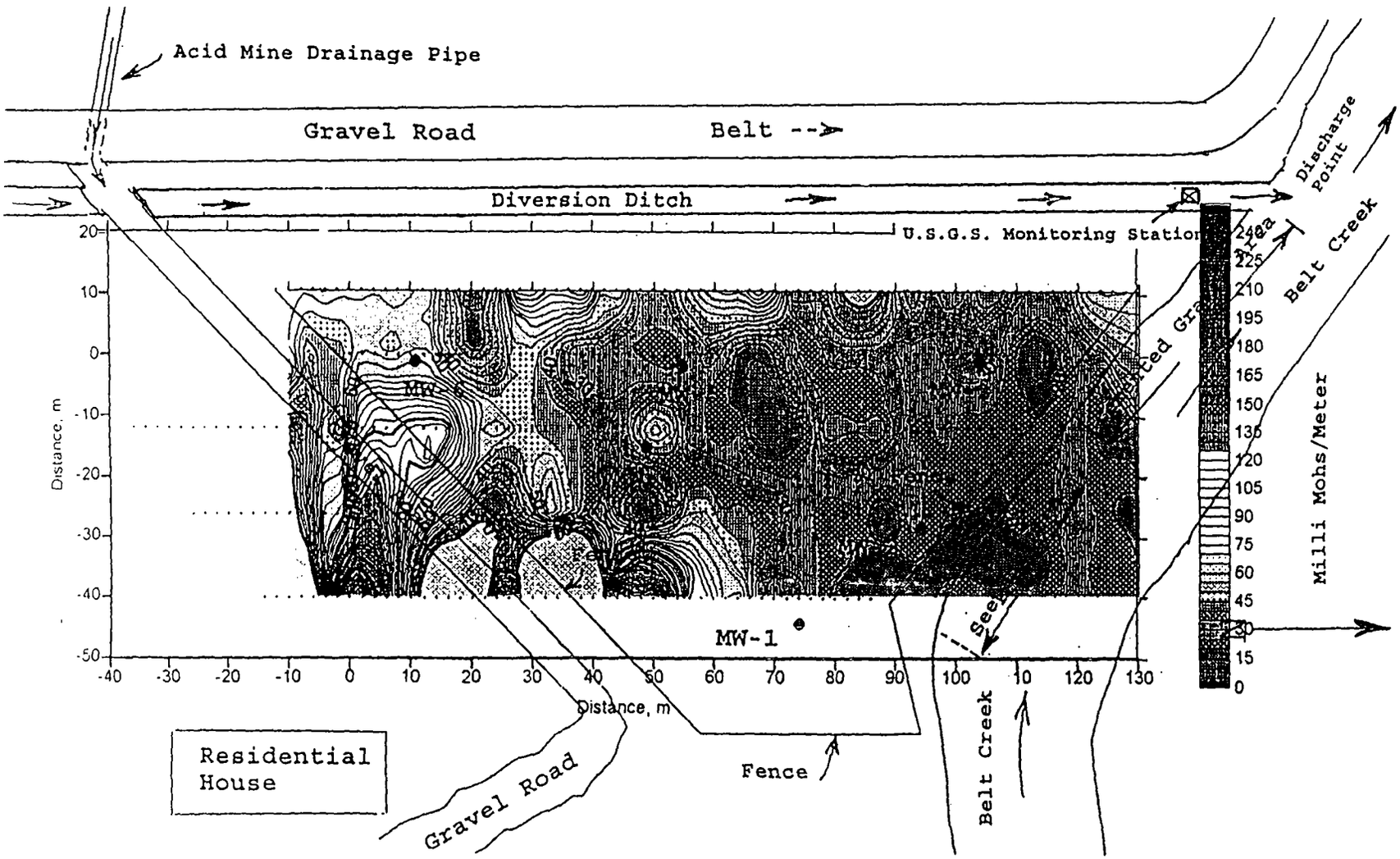

Figure 3. Geophysical Survey, EM34, Vertical Dipole, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

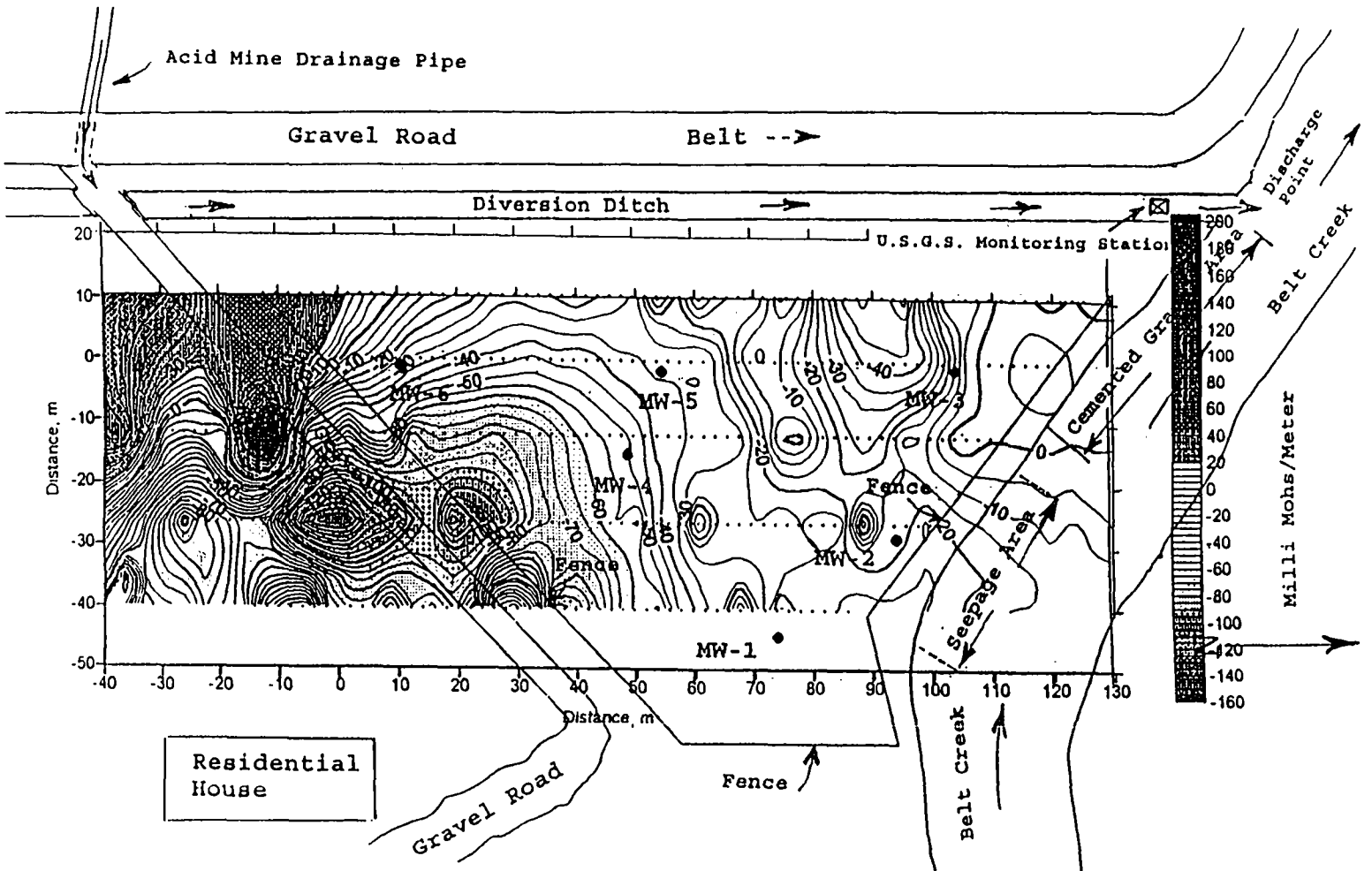

Figure 4. Geophysical Survey, Self-potential, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

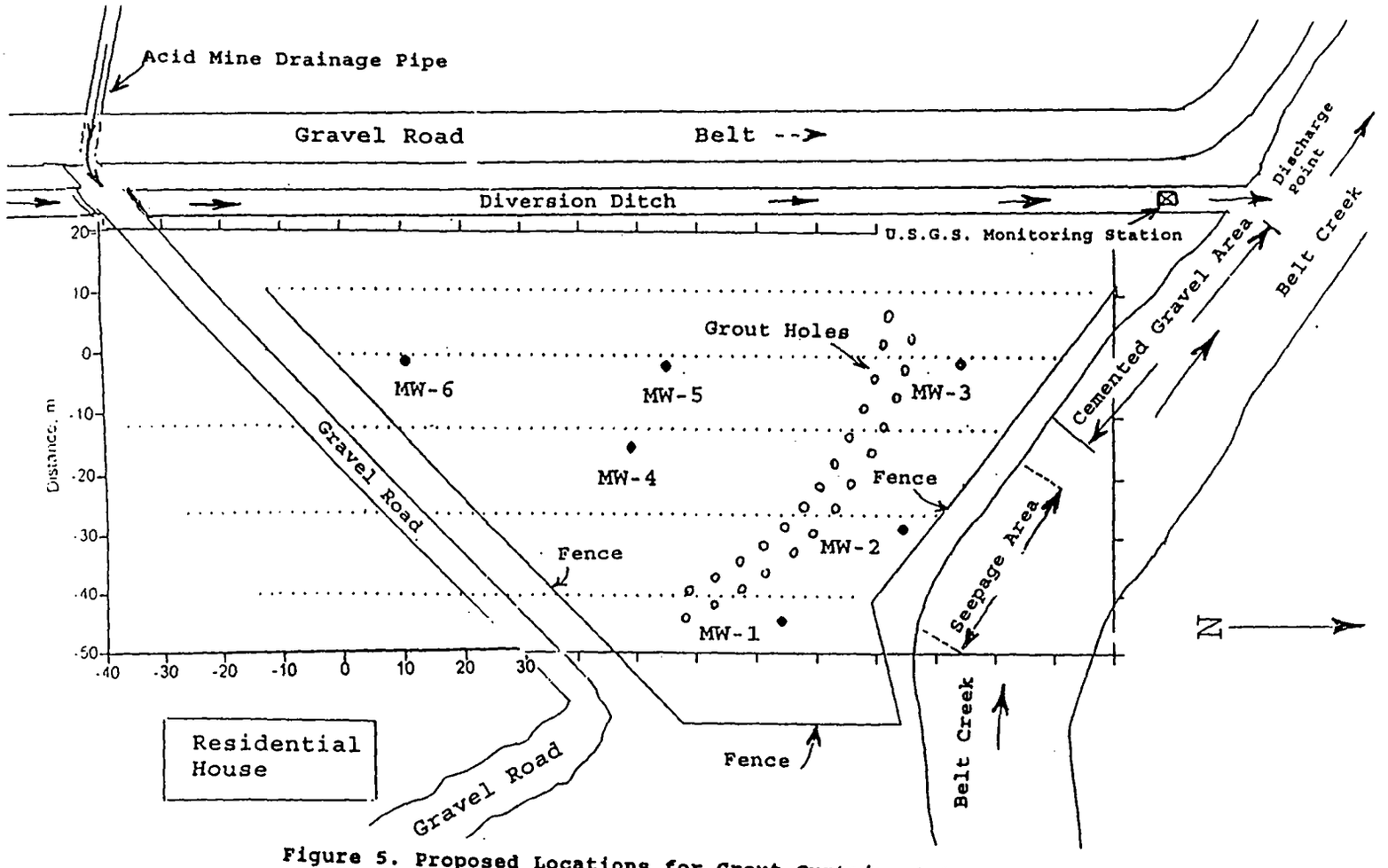

Figure 5. Proposed Locations for Grout Curtain at Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.