Methane Reduction through the Modeling of an Open Pit Coal Mine as a Packed Bed Reactor

Major Qualifying Project

Submitted to the Faculty

Of the

Worcester Polytechnic Institute

In partial fulfillment for the

Degree of Bachelor of Science

Submitted to

Jennifer Wilcox

By

Daniel Maynard

Abstract

Transitioning to a low-carbon economy under the recent U.S. climate change mandate presents an enormous challenge but is necessary to meet climate change goals of a 50-52% reduction in greenhouse gas emissions by 2030. One step towards building such an economy is the remediation of abandoned coal mines. According to the EPA abandoned coal mine database, there are currently 514 coal mines leaking methane into the atmosphere. These abandoned mines present an opportunity to create jobs as well as assist in the transition towards a low-carbon economy. One option for remediation is utilizing waste alkaline material as a physical barrier for CH_4 to reduce emissions. This paper proposes modeling abandoned open-pit coal mines as packed bed reactors using waste alkaline materials such as coal fly ash as the packing material in order to reduce or prevent methane leakage into the atmosphere. This paper found that substantial emission reductions are possible with back filling of an open pit mine with waste alkaline material.

Acknowledgement

I would like to thank my advisor Dr. Ben Kolosz for his support and feedback over the course of this project. I would like to also thank Katherine Gomes and Dr. Daniel Nothaft for assistance in developing the model for this project . Finally, I would like to thank Prof. Jennifer Wilcox for her support and providing me with the opportunity to explore this topic.

Contents

Introduction

In the U.S. there are many abandoned coal mines. Each of these coal mines are leaking methane (CH_4) into the atmosphere in varying quantities due to the unique properties of each mine. This is concerning because methane is a greenhouse gas that contributes to global warming. In fact, methane has a global warming potential 28 times that of carbon dioxide over a 100-year period. This rises to 86 times when projected over a shorter 20-year period (Pachauri & Meyer, 2014). The EPA estimates abandoned coal mines in the US leak 368,000,000 m^3 of methane per year, which is roughly 6,600,000 tons of CO_2 equivalents (CO_2e) (Cote, Collings, Pilcher, Talkington, & Franklin, 2004).

Despite the large amount of methane being emitted from these mines, few methane recovery operations exist. The Environmental Protection Agency (EPA) identifies 514 abandoned coal mines that are leaking methane into the atmosphere and 79 of these mines were identified as candidates for methane recovery due to their high emissions which were greater than 0.2 million of cubic feet per day (mmcfd) (US Environmental Protection Agency, 2017). Of these 79 mines, only 32 have existing methane recovery projects. While some progress has been made, this still leaves over half of the highest emitting mines without methane recovery mechanisms.

To help decrease these emissions, this report explores the possible backfilling of abandoned open-pit surface mines with waste alkaline materials such as coal fly ash. The mine acts as a packed bed reactor where the methane flow is reduced due to the waste alkaline material. This situation can be modeled using packed bed reactor design equations alongside several assumptions. The calculation assumptions can be found in appendix A.

To ensure that the scope of this project was tractable, only open-pit mines were considered and the study was focused on Pennsylvania. The reason for narrowing the scope only to Pennsylvania is due to the pre-existing mine-remediation processes, the readily available waste alkaline material from coal-fired plants, and the surrounding infrastructure of railways interconnecting the mines to the power plants. These pre-existing railways can be used to transport the alkaline material to the mine. After inspecting the EPA abandoned mine database there is one mine in Pennsylvania that stood out as a promising candidate for the proposed model due to it being an open pit mine, having high methane emissions, and existing methane recovery for comparison purposes. This mine is the Cambria Slope No. 33 mine (US Environmental Protection Agency, 2017).

Background

Section 1: Mining Overview

1.1: Mining Options

Today mining is done using one of three options: surface mining, underground mining, or *In-Situ*.

Open pit mining is a type of surface mining that involves extracting rocks or minerals from an open pit. It is the method of choice when the characteristics of the ore make the removal of overburden cost effective. When the desired ore is close to the surface, it is generally more economical to use an open pit mine. This is because the closer to the surface the mineral is the thinner the layer of overburden, or surface material. An example of an open pit mine is a quarry (Ceto & Mahmud, 2000)("Open-pit Mining," n.d.).

Another mining method is underground mining. Typically, this method is used when the removal of overburden is too great or uneconomical. Underground mining involves tunneling into the ground to reach the ore deposits below. Underground mining generally has significantly less impact on the surface environment than surface mining does. However, large underground workings, when abandoned, have sometimes caused subsidence or caving at the surface, resulting in disturbance to structures, roads, and surface water drainages (Ceto & Mahmud, 2000).

Lastly, there is *in-situ* mining which is a method of extracting minerals by injecting solvents into mineral deposits. Typically, this is done by drilling into the mineral deposit and circulating a solvent such that the ore dissolves and can be recovered in downstream processing. The solvent will vary depending on the ore being extracted as will the downstream processing to extract the ore from solution. This method of mining is rather uncommon, but it is one of the methods used to mine uranium (Ceto & Mahmud, 2000)("In Situ Leach Mining of Uranium," n.d.).

1.2: Mining Wastes

There are three general types of mine waste: overburden, mine water, and waste rock. Usually, most of the waste lies in mine water and waste rock, but in the case of surface mining overburden takes up a significant portion.

Overburden is all the surface material above the ore that gets removed. Surface material can be a variety of things, but in general it would be topsoil and rock. After the overburden is removed, the topsoil is stored and stockpiled to be used in the remediation process after the mine is closed.

Mine water consists of any source of water that enters a surface or underground mine. Examples include ground water seepage, surface water inflow, and direct precipitation. Mine water will need to be drained from the mine, either naturally or by pumping the water out. Mine water is an important aspect of mine management because, for an open pit mine, if it were to rain the water at the bottom of the mine would need to be removed. Otherwise, the mine would be unable to continue operating, and any future precipitation would continue to build and could potentially flood the whole mine. This water can be discharged from the mine into surface waters but has to conform to the regulations of the National Pollutant Discharge Elimination System (NPDES) (Ceto & Mahmud, 2000). Depending on the ore being mined and the type of mining processes, this water can be highly acidic or have other contaminants. Once the mine is no longer operational, water drainage stops. The water that inevitably seeps back into the mine will sit there until it is drained. While the water sits within the mining environment, this water can become highly acidic or accumulate heavy metals. If this occurs, it could be dangerous for downstream groundwater or surface water.

Waste rock consists of non-mineralized and low-grade mineralized rock from extraction activities. Low-grade mineralized rock means rock that has a too dilute a concentration of ore to be economical to extract. The size of waste rock varies, ranging from fine sand to large boulders. Waste rock geochemistry will vary depending on the ore being mined; waste rock from metal mines often contains sulfuric material. Sulfuric rock is prone to acid generation, which much like the mine water, will have an adverse effect on the nearby land (Ceto & Mahmud, 2000).

Figure 1 below helps to show the difference between overburden and waste rock.

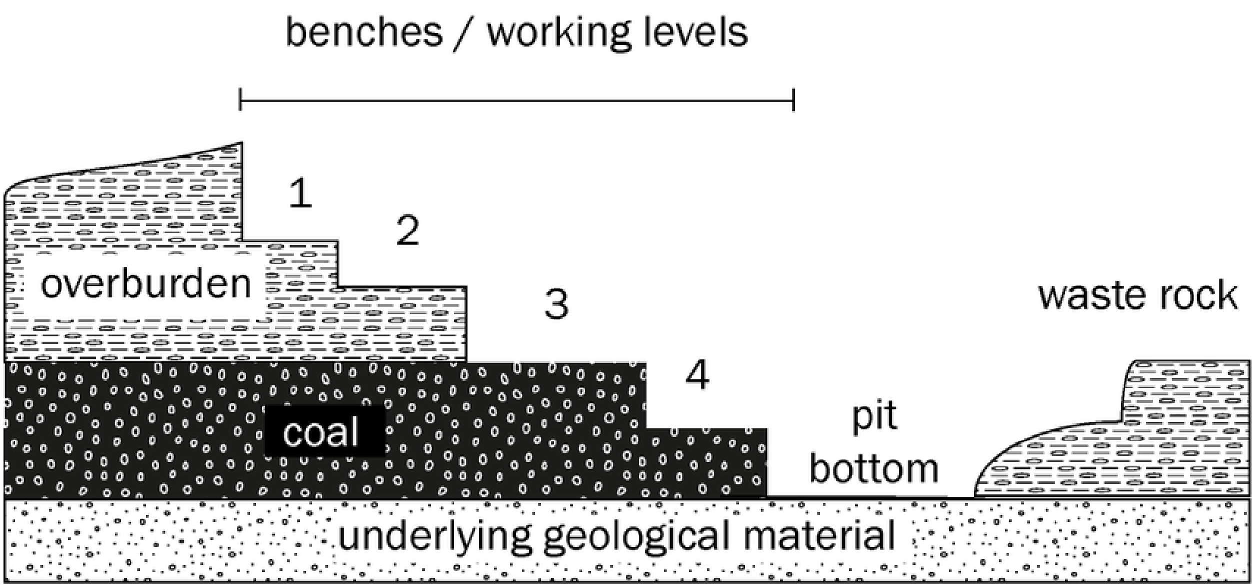

Figure 1: Picture showing how overburden and waste rock are categorized ((Marquez, 2013).

Section 2: Mine Remediation Options

Mine remediation is a complicated process that usually involves several remediation techniques working together to restore a mine. There are three categories of techniques used in remediation: conventional technologies, innovative/emerging technologies, and institutional controls.

Conventional technologies are techniques that have a successful track record in mine remediation. These are considered to be standard practice for mine site cleanup. Innovative technologies are ones that require more field testing and pilot-scale testing but show promise in mine remediation. Finally, institutional controls are less technology-based and concern strategies to protect human and environmental life.

2.1: Conventional Technology Treatment Overview

Conventional remediation technologies have been compiled into table 1 alongside their relative costs. A more in-depth discussion of the specifics of the technologies is below. Additional tables from the EPA's Abandoned Mine Site Characterization and Cleanup Handbook are provided in Appendix D.

Table 1: Shows Conventional technologies and their relative cost range

Technology	Relative Cost Range
Chemical Treatment	Low – High
Stabilization	Medium – High
Solidification	Medium – High
Thermal Desorption	Medium – High
Thermal Destruction	Medium – High
Vapor Extraction	Medium – High
Solvent Extraction	Low – High
Soil Washing	Medium – High
Soil Flushing	Medium – High
Decontamination of Buildings	Low – High

In this section, the merit of conventional technology treatment options will be discussed. Treatment technologies are remediation processes that change the composition of the target contaminant or limit contaminant mobility by mechanical and chemical means. This is in hopes of either eliminating or reducing the dangers to human and environmental life. Contaminant in this sense refers to the organic and inorganic material found in abandon mines. In addition, a relative cost estimate will also be provided for each technology.

Chemical Treatment: Reagents are used to destroy or modify organic and inorganic contaminants, converting hazardous material into less environmentally damaging forms. It is generally used as a pretreatment process to enhance the efficiency of subsequent processes or in post-treatment of an effluent. Two common uses for chemical treatment are the treatment of acid mine drainage and metal recovery. The cost for this technology ranges from low to high. This is influenced by the type of chemicals used and the byproducts produced. Disposal of byproducts can be very expensive even if the reagents used are inexpensive.

Stabilization: Stabilization refers to processes that reduce the risk posed by waste by converting the contaminants into a less soluble, less mobile, and less hazardous form without necessarily changing the physical nature of the waste. The cost of stabilization ranges from medium to high. This is dependent on the treatment required for stabilization to be effective.

Solidification: Solidification refers to processes that trap waste in a solid matrix of high-structural integrity. This technology does not require chemical interactions between the waste and the solidifying reagents but does involves physically binding the waste and binding material. There is a risk that the matrix containing the contaminants will breakdown over time potentially releasing dangerous material into the environment. The effectiveness of this technology is dependent on the encapsulating materials resists to breaking down over time. Typically, the cost of this technology ranges from medium to high. An example of a medium cost solidification would be using a matrix like cement to encapsulate contaminants.

Thermal Desorption: Thermal desorption refers to treatment that uses heat to remediate contaminated soils, sediments, and sludges. This method is used to separate a contaminant from the containing media by heating the material to within its gas-phase. The temperatures utilized for thermal desorption are usually high enough that organic material will undergo thermal destruction. This technology is not commonly used because the contaminants at mines are generally heavy metals and these cannot be heated to gas-phase. The off-gas from this process will also have to undergo further treatment: the effectiveness of this technology is usually poor due to the limiting factor of having to heat material to gas-phase temperatures. The cost of thermal desorption ranges from medium to high.

Thermal Destruction: Similarly, to thermal desorption there is thermal destruction. Thermal destruction typically uses higher temperatures to decompose contaminants, potentially with no hazardous contaminant residues or off-gas requiring further management. This technology is also not commonly used because the most common contaminants are metals, and they will not be destroyed by this process. The cost ranges from medium to high.

Vapor Extraction: Vapor extraction is an *in-situ* process that uses vacuum technology and subsurface retrieval systems to remove contaminant materials in their gas-phase. Vacuum extraction of vapors from contaminated soils and subsurface strata has been successfully employed to remove volatile compounds from permeable soils. Typically used at mines where chlorinated solvents or petroleum products have seeped into the subsurface. This technology is not useful when the primary contaminants are metals. The cost ranges from medium to high.

Solvent Extraction: Solvent/chemical extraction is an *ex-situ* separation and concentration process in which a nonaqueous liquid reagent is used to remove organic and/or inorganic contaminants from wastes, soils, sediments, sludges, or water. The cost ranges from low to high dependent on several factors: media necessary for extraction, the system to recover the solution, the process to remove the contaminants, and handling and disposal of spent waste or soil.

Soil Washing: The *ex-situ* process of soil washing employs chemical and physical extraction and separation techniques to remove a broad range of organic, inorganic, and radioactive contaminants from soils. The contaminated soil is excavated and mechanically screened, removing oversized material and separating into coarse and fine-grained fractions. These fractions are scrubbed and washed to removed surficial contaminants. The wash can use water or another liquid depending on remediation needs. The fractions then need to be treated using another technology to further remove contaminants. Generally, the fine fraction contains a significant portion of the contaminants and the washed soil can be used as backfill. The cost of this technology ranges between medium to high. This is influenced by the liquid recovery method and excavation costs.

Soil Flushing: The *in-situ* process of soil flushing uses water, enhanced water, or gaseous mixtures to accelerate the mobilization of contaminants from a contaminated soil for recovery and treatment. This method helps to accelerate geochemical dissolution reactions. This also helps to speed up subsurface transport mechanism such as advection and diffusion. After flushing the soil the fluid can be removed by natural seepage or a water recovery system. The cost of this technology ranges from medium to high. This is dependent on the characteristics of the soil and the type of fluid used for flushing.

Decontamination of Buildings: Decontamination of buildings and other structures through various extraction and treatment techniques may be necessary at certain mining and mineral processing sites. The purpose of decontaminating the structures may be to meet the requirements of historical preservation and/or to assist the community in attracting new industry. The cost will range from low to high depending on the required cleaning techniques.

2.2: Collection, Diversion, and Containment Technologies

If treatment technologies are insufficient in controlling contaminants to acceptable levels other methods are need. When this occurs collection, diversion, and containment technologies are used to contain or capture contaminants. These technologies are engineering controls that aim to reduce contaminant releases.

Table 2: Shows Collection, Diversion, and Containment Technologies along with their relative cost ranges.

Technology	Relative Cost Range
Landfill Disposal	Medium – High
Slurry Walls	Medium
Cement Walls	Medium – High
Sheet Pilings	Medium – High
Pumping Groundwater	Medium – High
Capping	Low – High
Detention/Sedimentation	Low – Medium

Settling Basins	Low – Medium
Interceptor Trenches	Low – Moderate
Wind Breaks	Low – Medium
Diversion	Low – Medium
Stream Channel Erosion Controls	Low – High

Landfill Disposal: Landfills are waste management units, usually dug into the earth, but can be above ground that accept waste for permanent placement and disposal. Landfills may be lined to contain leachate, drained with a leachate collection system, and capped. This does have an added risk of breaching the lining which would mean the landfill is no longer containing the contaminants. The cost of landfills ranges from medium to high.

Cutoff Walls: Cutoff walls are structures used to prevent the flow of ground water from either leaving an area, in the case of contaminated ground water, or entering a contaminated area, in the case of clean ground water. There are three types of cutoff walls: slurry walls, cement walls, and sheet piling.

> **Slurry Walls:** trenches refilled with a material that combines low permeability and high adsorption to impede the passage of ground water and associated contaminants. The cost is in the medium range.
> **Cement Walls:** Similarly, to slurry walls, except instead of low permeability clay-like slurry, cement-based slurry is used. The cost ranges from medium to high but has increased efficiency.
> **Sheet Piling:** Technology often used to install a cutoff wall. Sheet piling has been used in the past to funnel ground water to a treatment cell for treatment and is regularly used as a temporary cutoff wall during remediation period. The cost ranges from medium to high.

Pumping Groundwater: A pump-and-treat process for addressing groundwater contamination is a combination of an extraction technology and a subsequent treatment technology. The treatment, which can vary by contaminant, could be any of the other technologies discussed above. The pump-and-treat technology has been the preferred method of remediating contaminated ground water. The cost ranges from medium to high.

Capping: Capping is typically used to cover a contaminated area or waste unit to prevent precipitation from infiltrating an area, to prevent contaminated material from leaving the area and to prevent human or animal contact with the contaminated materials. The cost ranges from low to high. Primarily depending on the type of cap used.

Detention/Sedimentation: Detention/sedimentation controls are used to control erosion and sediment laden runoff. Treatment generally consists of slowing the water flow and reducing the associated turbulence to allow solids to settle out. Settling may be allowed at natural rates; in other cases flocculants may be added to increase the settling rate. The settled sediments may be removed and disposed; if the sediment is contaminated then treatment may be required. A flocculant is a substance that promotes clumping of particles. The cost ranges from low to medium.

Settling Basins: Settling basins may be used to contain surface waters so that contaminated sediments suspended in the water column can be treated, settled, and managed appropriately. Dissolved contaminants and/or acid waters may be contained as well to allow for treatment or natural degradation. The cost ranges from low to medium.

Interceptor Trenches: Interceptor trenches are trenches that have been filled with a permeable material, such as gravel, that will collect the ground water flow and redirect it for either *in-situ* or *ex-situ* treatment. Interceptor trenches are often used to collect and treat ground water and prevent it from leaving a containment area, such as a landfill. The cost ranges from low to moderate.

Erosion Controls: Erosion controls are those engineering controls used to eliminate or minimize the erosion of contaminated soils by either air or precipitation. These controls are:

> **Capping or Covers:** This is the same as previously discussed.
> **Wind Breaks:** Used to minimize the erosion of soils and dusts by the wind and can include planting of trees and other vegetation to reduce the wind velocity, and/or the installation of fences. The cost low to medium
> **Diversion:** Used to control surface water around areas that have a high probability of erosion. Divert ground water or surface water from infiltrating waste units or areas of contamination, thereby preventing the media from being contaminated and pollutants from leaching and migrating. The cost ranges from low to medium

Stream Channel Erosion Controls: Used to minimize the mobilization and transport of contaminated sediments by streams within the site. Technologies to control stream channel erosion often include both erosion controls and diversions such as channelization or lining of stream channels, diversion dams and channels. The cost ranges from low to high.

During the process of remediation some useable material might be recovered. These materials can be sold to help reduce the cost of remediation. Recycling and reusing these materials is another effective method of eliminating contaminants and reducing remediation cost. However, this is not necessarily applicable to all remediation projects.

2.3: Innovative/Emerging Technologies

As mentioned above there are innovative/emerging technologies for mine remediation. This section will discuss a few of these technologies.

Table 3: Shows Innovative/Emerging Technologies and their relative cost ranges.

Technology	Relative Cost Range
Bioremediation	Medium – High

Phytoextraction	Low – Medium
Rhizofiltration	Low – Medium
Phytodegradation	N/A
Vitrification	Very High

Bioremediation: Use of microbiota to degrade hazardous organic and inorganic materials to innocuous materials. Cost ranges from medium to high

Phytoremediation: Use of plants and trees to extract, stabilize or detoxify contaminants in soil and water.

> **Phytoextraction (Phytoaccumulation):** Uptake of metal contaminants by plant roots into stems and leaves. Plants that have the ability to absorb large amounts of metal are planted at the remediation site. Once done the plants are harvested and either incinerated or composted to recover the metal. The cost ranges from low to medium.
>
> **Rhizofiltration:** Used to remove metal contamination in water. Roots of certain plants take up contaminated water along with the contaminants. Once the roots are saturated with contaminate the plants are harvested and disposed of. The cost ranges from low to medium.
>
> **Phytodegradation:** Is a process in which plants are able to degrade organic pollutants. Phytodegradation is not currently used for inorganic contaminants.

Vitrification: Vitrification is a solidification process employing heat to melt and convert waste materials into glass or other crystalline products. Metal is incorporated into glass structure. The high temperatures destroy any organic constituents with byproducts treated in an off-gas system. This method is very effective at isolating waste, but also has a very high cost.

Section 3: Acid Mine Drainage

Mining has several environmental concerns related to it, but one commonly shared one is acid mine drainage (AMD). AMD is the natural acidification of mine water. AMD occurs due to the oxidation of sulfuric minerals with water and/or O_2. This process varies significantly regarding time and severity, primarily relying on the mineralogy of the waste rock, availability of water, and oxygen. AMD can be even further accelerated depending on the type of micro-organisms existing in the mine water. All of these factors considered the formation of AMD can be very rapid or take years even decades. Table 4 shows a list of sulfide minerals and the below reactions demonstrate AMD with pyrite (Ceto & Mahmud, 2000)(US Environmental Protection Agency, 1994).

Mineral	**Composition**
Pyrite	FeS_2
Marcasite	FeS_2
Chalcopyrite	$CuFeS_2$

Chalcocite	Cu_2S
Sphalerite	ZnS
Galena	PbS
Millerite	NiS
Pyrrhotite	$Fe_{1-x}S$ (where 0<x<0.2)
Arsenopyrite	$FeAsS$
Cinnabar	HgS

Table 4: List of sulfide minerals that react in AMD. Adapted from (US Environmental Protection Agency, 1994)

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O \quad (2)$$

$$Fe^{2+} + \frac{1}{4}O_2 + \frac{5}{2}H_2O \rightarrow Fe(OH)_3 + 2H^+ \quad (3)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (4)$$

This process results in the percolation of water that has a low pH and high metal concentration. AMD introduces sulfuric acid and heavy metals into the environment. The environment does have some capacity to treat AMD, but it is limited and once that limit is reached the AMD water will be discharged from the mine and can lead to ground water contamination. Ground water contamination is both an environmental and health concern as microscopic and macroscopic life are very sensitive to pH change and can be poisoned by elevated concentrations of heavy metals (US Environmental Protection Agency, 2017)(US Environmental Protection Agency, 1994). This being the case, mine remediation is generally the treatment option. AMD can be remediated by neutralizing the acids in the water and removing heavy metals. The acids can be neutralized by using lime ($CaCO_3$) and the heavy metals can removed using a separation process. Below is the neutralization reaction of lime in acidic conditions (US Environmental Protection Agency, 2017)(US Environmental Protection Agency, 1994).

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \quad (6)$$

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \quad (7)$$

AMD can be neutralized using other alkaline material, which poses a co-benefit of the processes investigated by this study because these alkaline materials can be byproducts of other industrial process. For example, coal fly ash, steel slag, and cement kiln dust are viable options for AMD neutralization and remediation. AMD is especially relevant when talking about coal mines because coal contains sulfide minerals. As evident from chemical equations 1, 2, 3, and 4 sulfide plays a substantial role in AMD generation.

Methodology

To model an open-pit mine as a packed bed reactor there are several considerations that have to be addressed. First is the mass-transfer that takes place at these mines. Figure 2 below is a simplified model of what the mass transfer of an open-pit mine would be.

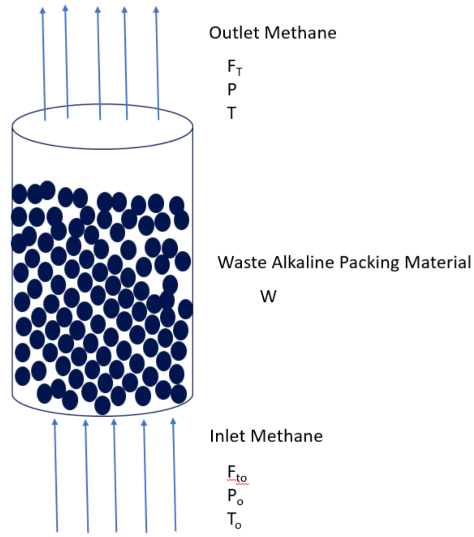

Figure 2: Depicts one-dimensional mass transfer of an open-pit mine

The mass transfer for this model is considered to be one-dimensional. This means the methane leaks from the bottom of the mine up through the waste alkaline material and then exits into the atmosphere. The reason for the one-dimensional mass transfer is to limit cross-sectional areas to simple shapes like a circle, rectangle, or triangle.

Next, the geometry of the mine needs to be determined in order to calculate the volume and surface area. In general, an open-pit mine's geometry can be described as a right circular cone as shown in figure 2 with a cross-sectional area of a circle ("Appendix B. Open Pit Geometry," n.d.).

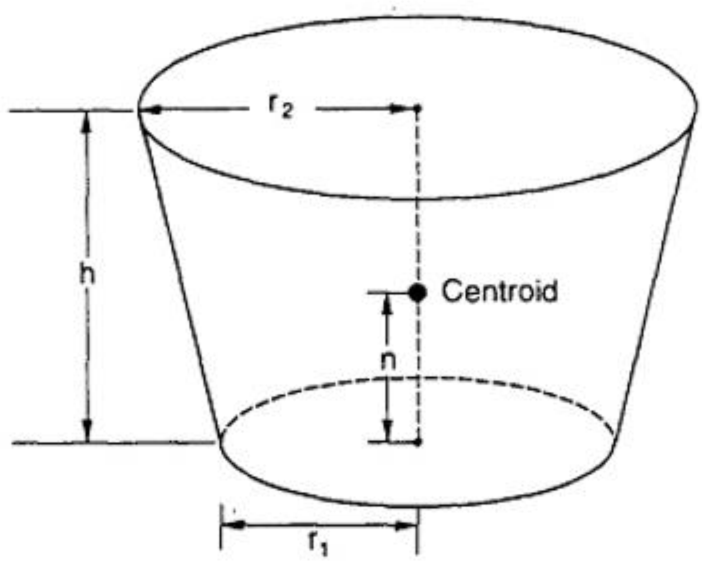

Figure 3: General geometry of an open-pit mine

This geometry is accompanied by the following equations.

$$V = \frac{1}{3}\pi h(r_1^2 + r_2^2 + r_1 r_2) \quad (8)$$

$$r_1 = 0.6h \quad (9)$$

$$r_2 = 1.6h \quad (10)$$

However, this geometry does not fit the geometry of Cambria Slope. The geometry of Cambria slope is closer to a rectangular prism as shown by figure 4.

Figure 4: Google Earth picture of Cambria Slope No. 33

The geometry of Cambria slope is of an irregular shape, but a rectangular prism seemed to fit better than the geometry of a right circular cone and as such the cross-sectional area is considered to be a rectangle. The measurements for the mine were found using the measurement tool in Google Earth. The mine is estimated to have a length of 1,700 meters, a width of 600m, and a height of 10 meters. This gives a volume of 10,200,000 m^3 and a cross-sectional area of 1,020,000 m^2.

Finally, to model the diffusion of methane through the waste alkaline material the Ergun equation was used. The Ergun equation is used to describe the pressure drop of a reactor per length of the reactor and described by the below equation (Wilcox, 2012)(Rosen, 1999)

$$\frac{\Delta P}{L} = \frac{150 u_o \mu (1-\varepsilon)^2}{D_p^2 \varepsilon^3} + \frac{1.75 \rho u_o^2 (1-\varepsilon)}{D_p \varepsilon^3} \quad (11)$$

ΔP is the pressure drop, L is the height of the mine. u_o is the superficial velocity of methane. μ is the viscosity of methane. ε is void space estimated to be 0.3 (Wilcox, 2012). D_p is the particle diameter of the waste alkaline material, which is assumed to be 1 micron, and ρ is the density of methane. The superficial velocity can be determined by dividing the volumetric flow of methane with the cross-sectional area of the mine. Using the Ergun equation, it can be combined with the ideal gas law to get the pressure drop per length of the packed bed. The below equation shows this relationship (Wilcox, 2012)(Rosen, 1999).

$$\frac{\Delta P}{L} = \beta_o \frac{P_o T F_T}{P T_o F_{To}} \qquad (12)$$

β_o is the entirety of the Ergun equation. P_o is the pressure of the coal seam. T is the temperature at the top of the mine. F_T is the methane flow out of the mine. P is atmospheric pressure. T_o is the temperature at the bottom of the mine. F_{To} is the methane emissions from the mine. The pressure inside a coal seam is estimated to between 1.58 MPa and 2.36 MPa (Zhang, Wu, Pu, He, & Li, 2018). Taking the equation one step further, the height of the mine can be converted to the expected weight of the waste alkaline material. This is shown in equation 13.

$$\frac{\Delta P}{W} = \frac{\beta_o}{A_c(1-\varepsilon)\rho_c}\left(\frac{P_o T F_T}{P T_o F_{To}}\right) \qquad (13)$$

W is the waste alkaline material weight and can be determined by multiplying the mine volume by ρ_c. A_c is the cross-sectional area of the mine. ρ_c is the waste alkaline material density. Using this final equation, the outlet flow of methane is the only unknown and is solved for in this project. Sample calculations can be found in appendix B along with the physical properties of methane.

To determine a time frame for these projects, the Mine Safety and Health Administration (MSHA) mine data retrieval system was used ("Mine Data Retrieval System," n.d.). Using the MSHA ID from the EPA abandoned coal mine database a variety of data can be acquired including the production and number of workers at a mine. All of the active coal mines in Pennsylvania were compiled into an excel sheet with the data from the MSHA site as well. From this the average production of a miner was calculated by taking the total production of all the mines and dividing by the number of miners.

Results & Discussion

For the Cambria slope mine with a rectangular prism geometry the volume was found to be 10,020,000 m^3. Using the density of coal fly ash, the total weight required to fill the mine is 29,000,000 tons of coal fly ash. By changing the quantity of waste alkaline material, the following results were obtained.

Table 5: Table shows the percentage of emission reduction for a given alkaline weight.

Percentage Filled	Alkaline Weight (tons)	Entering Methane Flow (m^3/day)	Exit Methane Flow (m^3/day)	Avoid Emissions (m^3/day)	Percent Reduction
100	29,000,000	134,000	20,000	114,000	85
75	22,000,000	134,000	26,000	108,000	81
50	15,000,000	134,000	39,000	95,000	71
25	7,300,000	134,000	78,000	55,000	42
29.2	8,500,000	134,000	67,000	67,000	50

Table 5 shows how the methane emissions reduction for the mine changes as the amount of waste alkaline material used varies. As expected, the amount of methane emissions avoided decreases as the amount of waste alkaline material is decreased. However, this relationship is not linear. Decreasing the percentage filled from 100% to 50% causes the methane emissions reduction to drop from 85% to 71% (14% total). Additionally, the final row demonstrates that to get 50% reduction in emissions the mine needs to be filled 29% of the total weight.

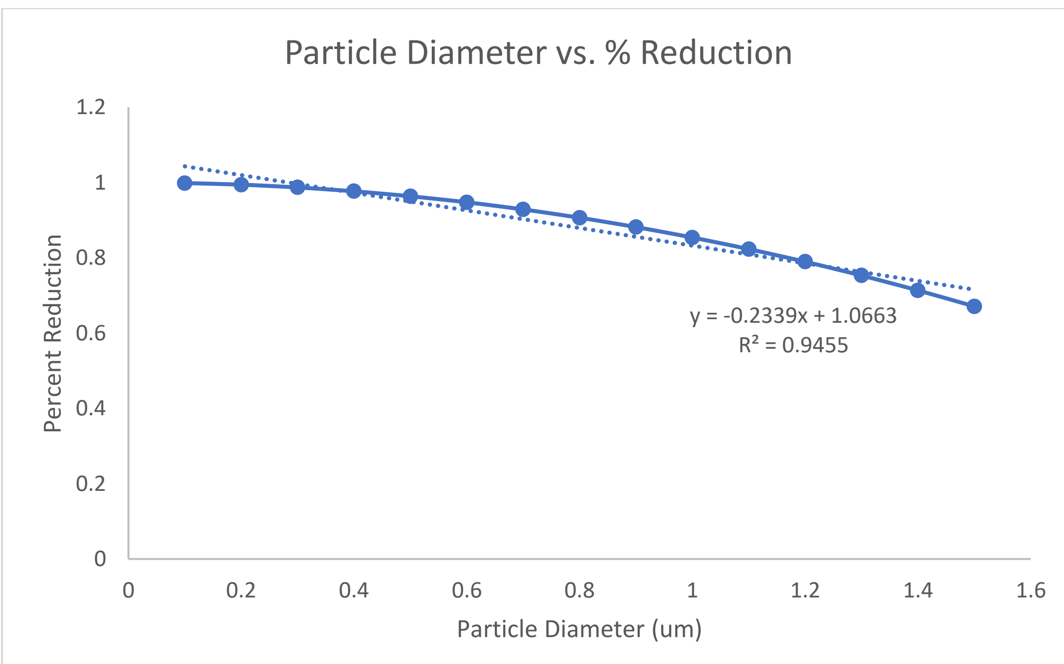

Figure 5: Graph of particle diameter versus percent reduction for a 100% filled mine.

Additional analysis was done to determine the effect the particle diameter had on the reduction percentage. Figure 5 illustrates that particle diameter has a substantial impact on the reduction percentile. Also, as particle diameter increases the percent reduced decreases. This is to be expected as increasing the particle size decreases the number of individual particles and ultimately decreases the total surface area of all particles. The same analysis was done but with only 50% of the mine filled. Figure 5 demonstrates that as the mine is less filled the effect particle diameter is more significant. It is important to note that figure 5 uses a range of 0.1 to 1.5 microns for its particle diameter. These are very small particle diameters and this is due to the model not being to work with larger particle sizes yet. The model requires refinement to be able to handle larger particle sizes. This is evident from the increase in the slope of the trendline. Additional graphs are available in appendix C.

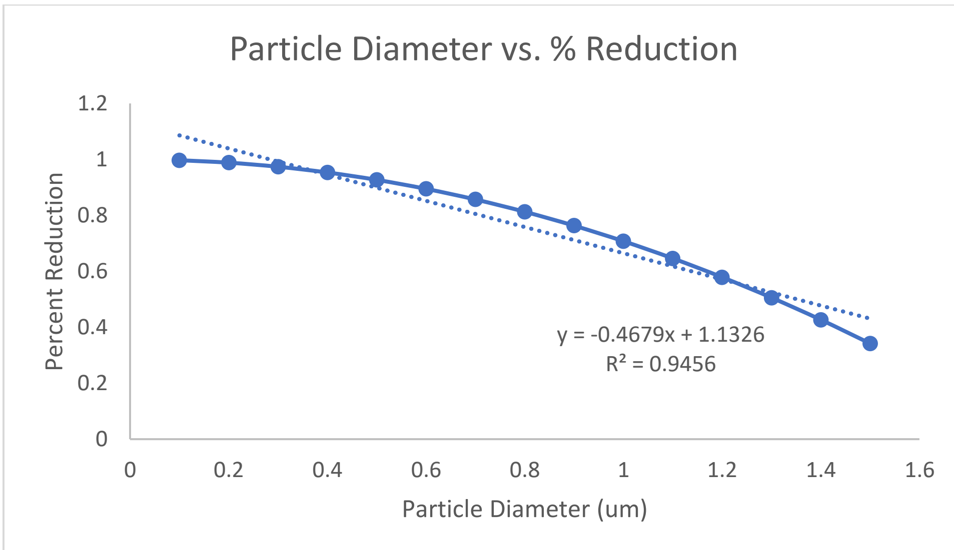

Figure 6: Graph of Particle Diameter versus percent reduction with only 50% of the mine filled.

The geometry of the mine was changed to determine the effect of geometry on reduction percentage: right circular cone geometry was used. This also changed the cross-sectional area of the mine to a circle. This theoretical mine has height of 136 meters, a top radius of 217 meters, and a bottom radius of 82 meters. These dimensions keep the volume of the mine the same, but the cross-sectional area changed to 150,000 m^2. This was calculated using the top radius of 217 meters. The following results were obtained using a particle diameter of 1 micron.

Table 6: Shows percent emission reduction for a mine with the geometry of right circular cone and a particle diameter of 1 micron.

Percentage Filled	Alkaline Weight (tons)	Entering Methane Flow (m^3/day)	Exit Methane Flow (m^3/day)	Avoid Emissions (m^3/day)	Percent Reduction
100	29,000,000	134,000	415	133,525	99.7
75	22,000,000	134,000	552	133,386	99.6
50	15,000,000	134,000	829	133,109	99.5
25	7,300,000	134,000	1,659	132,280	98.8

Table 6 shows the results of using a 1 micron particle diameter with the right circular cone. These results show that any degree of filling will give a significant decrease in methane emissions. If such results were true this would be highly beneficial, but these results are most likely not the case in reality. The calculations were redone with a larger particle size this time using 8 microns.

Table 7: Shows percent emission reduction for a mine with the geometry of right circular cone and a particle diameter of 8 micron.

Percentage Filled	Alkaline Weight (tons)	Entering Methane Flow (m^3/day)	Exit Methane Flow (m^3/day)	Avoid Emissions (m^3/day)	Percent Reduction
100	29,000,000	134,000	26,500	107,500	80.2
75	22,000,000	134,000	35,000	99,000	73.6
50	15,000,000	134,000	53,000	81,000	60.4
25	7,300,000	134,000	106,000	28,000	20.7

Table 7 shows the results of a right circular cone open-pit mine with a particle diameter of 8 microns. The major findings of this table are that the right circular cone geometry can afford a larger particle size than the rectangular prism can. This is most likely due to the decreased cross-sectional area and more effective packing.

The packed bed reactor model was compared to the current methane recovery project at the Cambria mine. The methane recovery at the mine currently avoids 225 million cubic feet per year. This is equivalent to an avoided emission flow of 17,500 m^3/day.

Table 8: Table shows the percentage emission reduction for a given alkaline weight compared to the current remediation.

Percentage Filled	Alkaline Weight(tons)	Entering Methane Flow (m^3/day)	Exit Methane Flow (m^3/day)	Avoid Emissions (m^3/day)	Percent Reduction
100	29,000,000	134,000	20,000	114,000	85
75	22,000,000	134,000	26,000	108,000	81
50	15,000,000	134,000	39,000	95,000	71
25	7,300,000	134,000	78,000	55,000	42
29.2	8,500,000	134,000	67,000	67,000	50
16.8	5,000,000	134,000	117,000	17,500	13

Table 8 is similar to table 7 except that it illustrates how much the mine needs to be filled to achieve a 13% reduction in emissions like the currently active methane recovery situated at the mine. According to the model, a 13% reduction in emissions requires 5,000,000 tons of coal fly ash is needed. This is a lot of material to move in order to achieve such a small reduction. However, an additional 3,500,000 tons are required to achieve a 50% reduction in emissions. Reducing emissions by half is not an insignificant amount and it only takes 29% of the total mine capacity to achieve it. This suggests that there is an optimal weight that will achieve the most reduction for the least amount of material.

Finally, the timeframe to fill the mine to the different capacities was calculated yielding the following.

Table 9: Shows the time frame in years for completing the back filling

Percentage Filled	Alkaline Weight (tons)	Workers	Production (tons/day)	Reduction Percentage	Time to completion (years)
100	29,000,000	250	32.3	85	9.8
75	22,000,000	250	32.3	81	7.5
50	15,000,000	250	32.3	71	5.1
25	7,300,000	250	32.3	42	2,5
29.2	8,500,000	250	32.3	50	2.9

Table 9 shows the how long each of the different capacities would take assuming 250 workers are stationed at the mine with a production of 32.3 tons per day. This table helps to demonstrate that these back filling projects will take a significant amount of time to get a significant reduction of emissions.

Conclusion & Recommendations

The primary conclusion from this study is that current methane recovery practices at abandoned coal mines can be enhanced by utilizing waste alkaline materials as back fill. The potential avoided emissions are significant; using 8,500,000 tons of coal fly ash has the potential to reduce methane emissions by 50% at Cambria Slope mine #33. However, further analysis is needed because the relationship between waste alkaline weight and reduction percentage is not linear. At 100% capacity the reduction percentage is 85% but reducing the capacity to 50% does not reduce the reduction percentage by half; it is only reduced by 14%. The relationship between waste alkaline weight and reduction percentage seems to suggest that there is an optimal weight that has the largest reduction potential for the least amount of weight. This is important because filling the mine with 29,000,000 tons of coal fly ash might be possible, but it most likely is not feasible from both a time and economic standpoint. The time frame for this project is significantly long to fill the mine to 25% capacity and it would take 250 workers two and half years. Assuming a $23 per hour wage for each of these workers this project would cost between $35,000,000 and $118,000,000 depending how much alkaline material is used ("Quarry Worker

Salary," n.d.). This estimate excludes transportation costs. Taking into account that methane has a global warming potential of 28 over a 100 year timeframe, and with these cost estimates this would place the capture cost between $85 and $140 per ton of CO_2e. This cost is in the higher range of capturing as costs can get as low as $52 to $60 per ton (Schmetz, Hochman, & Miller, 2020). As it stands, the study suggests that there is significant emission reduction potential, but it would be very costly in terms of time and money.

There are a few recommendations that could improve these results. First, the model currently does not take into account an adsorption rate of methane onto the alkaline material. The model is purely based on physical characteristics of the alkaline material and methane. Utilizing an adsorption rate would help to improve the accuracy of the reduction percentage versus alkaline weight. Including an absorption rate will also help to determine how different waste alkaline materials will affect the reduction percentage. Second, a more in-depth economic analysis is required to determine if back filling with alkaline material is feasible from a time and economic standpoint. The estimations discussed above are very rough estimates based on averages and the production per day does not take into account the kind of work begin done. The production represents the coal mined per day per worker, but the work actually being done is not mining. This means the production could be higher or lower since the type of work is different. A more in-depth economic analysis is essential to gauging the feasibility of utilizing waste alkaline material in open-pit mines.

References

Appendix B. Open Pit Geometry. (n.d.). Retrieved May 5, 2021, from https://pubs.usgs.gov/usbmic/ic-9298/html/camm5n36.htm

Ceto, N., & Mahmud, S. (2000). Abandoned Mine Site Characterization and Cleanup Handbook. *United Sates Environmental Proctection Agency*, (August), 129 p.

Cote, M., Collings, R., Pilcher, R. C., Talkington, C., & Franklin, P. (2004). *Methane Emissions from Abandoned Coal Mines in the United States: Emissino Inventory Methodology and 1990 - 2002 Emissions Estimates*. (April), 90. Retrieved from http://www.epa.gov/coalbed/docs/amm_final_report.pdf

In Situ Leach Mining of Uranium. (n.d.). Retrieved May 5, 2021, from World Nuclear website: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx#:~:text=In situ leaching (ISL)%2C,the minerals can be recovered

Marquez, J. E. (2013). *Geochemical characterization of coal and mine rock waste samples from the region of Cam Pha in NE-Vietnam and their effect on rice paddy soil composition and toxic metal bioavailability*. (May), 83. https://doi.org/10.13140/RG.2.1.3301.2648

Mine Data Retrieval System. (n.d.). Retrieved May 5, 2021, from https://www.msha.gov/mine-data-retrieval-system

Open-pit Mining. (n.d.). Retrieved May 5, 2021, from Lumen website: https://courses.lumenlearning.com/geology/chapter/reading-open-pit-mining/

Pachauri, R. K., & Meyer, L. A. (2014). Climate Change 2014 Synthesis Report. In *IPCC* (Vol. 5).

Quarry Worker Salary. (n.d.). Retrieved May 5, 2021, from ZipRecruiter website: https://www.ziprecruiter.com/Salaries/Quarry-Worker-Salary#:~:text=As of Feb 24%2C 2021,%2Fweek or %243%2C867%2Fmonth.

Rosen, A. (1999). Reactor design. *Studies in Surface Science and Catalysis*, *124*(C), 163–183. https://doi.org/10.1016/S0167-2991(99)80302-4

Schmetz, W. J., Hochman, H., & Miller, K. G. (2020). Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States. *The Royal Society Publishing*. https://doi.org/https://doi.org/10.1098/rsfs.2019.0065

US Environmental Protection Agency. (1994). Acid Mine Drainage Prediction. *U.S Environmental Protective Agency*, (December), 52. Retrieved from https://19january2017snapshot.epa.gov/sites/production/files/2015-09/documents/amd.pdf

US Environmental Protection Agency. (2017). *Abandoned Coal Mine Methane Opportunities Database*. (July), 24.

Wilcox, J. (2012). Introduction to Carbon Capture. In *Carbon Capture*. https://doi.org/10.1007/978-1-4614-2215-0_1

Zhang, L., Wu, Y., Pu, H., He, X., & Li, P. (2018). The Migration of Coalbed Methane under Mining Pressure and Air Injection: A Case Study in China. *Geofluids*, *2018*. https://doi.org/10.1155/2018/4034296

Appendix A: Calculation Assumptions

- Assume the volume loss due to benches is negligible
- Assume cross-sectional area is a rectangle
- Assume one-dimensional mass transfer
- Assume no chemical interactions
- Assume no wetting of packing materials
- Assume isothermal
- Assume gas is almost entirely methane
- Assume void fraction is 0.3 (estimate from activated carbon)
- Assume Particle Diameter is 1 micron
- Assume coal seam pressure is between 1.58 and 2.36 MPa
- Assume steady-state

Appendix B: Sample Calculations

Mine Volume and Cross-sectional area (Rectangle):

$$V_m = l * w * h$$

$$A_c = l * w$$

$l = 1703.24\ m$

$w = 600.3\ m$

$h = 10\ m$

$$V_m = 1700 * 600 * 10 = 10{,}224549.72\ m^3$$

$$A_c = 1700 * 600 = 1{,}022{,}454.972\ m^2$$

Mine Volume and Cross-sectional area (Right circular cone):

$$V = \frac{1}{3}\pi h(r_1^2 + r_2^2 + r_1 r_2)$$

$$r_1 = 0.6h$$

$$r_2 = 1.6h$$

$$A_c = \pi r^2$$

$h = 136.01\ m$

$r_1 = 81.62\ m$

$r_2 = 217.62\ m$

$$V = \frac{1}{3} * \pi * 136.01 * (81.62^2 + 217.62^2 + 82.62 * 217.62) = 10{,}224{,}546.76\ m^3$$

$$A_c = \pi * 217.62^2 = 148{,}791.796\ m^2$$

Ergun Equation:

$$\frac{\Delta P}{L} = \frac{150 u_o \mu (1-\varepsilon)^2}{D_p^2 \varepsilon^3} + \frac{1.75 \rho u_o^2 (1-\varepsilon)}{D_p \varepsilon^3}$$

$\mu = 1.1 * 10^{-5}\ Pa * s$

ε = 0.3

$D_p = 1 * 10^{-6}\ m$

$\varepsilon = 0.3$

$u_o = 1.52 * 10^{-6} \frac{m}{s}$

$$\frac{\Delta P}{L} = \frac{150 * (1.52 * 10^{-6}) * (1.1 * 10^{-5}) * (1 - 0.3)^2}{(1 * 10^{-6})^2 * 0.3^3} + \frac{1.75 * (0.657) * (1.52 * 10^{-6})^2 * (1 - 0.3)}{(1 * 10^{-6}) * 0.3^3} = 37521.3 \frac{Pa}{m}$$

Waste alkaline Material Weight:

$$W = V_m * \rho_c$$

$V_m = 10{,}224{,}549.72\ m^3$

$\rho_c = 2600 \frac{kg}{m^3}$

$$W = 10{,}224{,}549.72 * 2600 = 26{,}583{,}829{,}272\ kg = 29{,}303{,}647\ tons$$

Methane Outlet Flow:

$$\frac{\Delta P}{W} = \frac{\beta_o}{A_c(1 - \varepsilon)\rho_c} \left(\frac{P_o T F_T}{P T_o F_{To}} \right)$$

Rearrange

$$F_T = \frac{\Delta P}{W} \left(\frac{F_{To} T_o P}{P_o T} \right) \left(\frac{A_c(1 - \varepsilon)\rho_c}{\beta_o} \right)$$

$\Delta P = 14.6\ atm$

$W = 26{,}583{,}829{,}272\ kg$

$F_{To} = 134{,}000 \frac{m^3}{day}$

$T_o = T$

$P = 1\ atm$

$P_o = 1.58\ MPa = 15.6\ atm$

$A_c = 1{,}022{,}454.972\ m^2$

$\varepsilon = 0.3$

$\beta_o = 37{,}521.3 \frac{Pa}{m}$

$\rho_c = 2{,}600 \frac{kg}{m^3}$

$$F_T = \frac{14.6}{26{,}583{,}829{,}272} \left(\frac{134{,}000 * 1}{15.6} \right) \left(\frac{1{,}022{,}454.972(1 - 0.3)2{,}600}{37{,}521} \right) = 19583.24 \frac{m^3}{day}$$

Appendix C: Graphs of Particle Diameter versus Percent Reduction

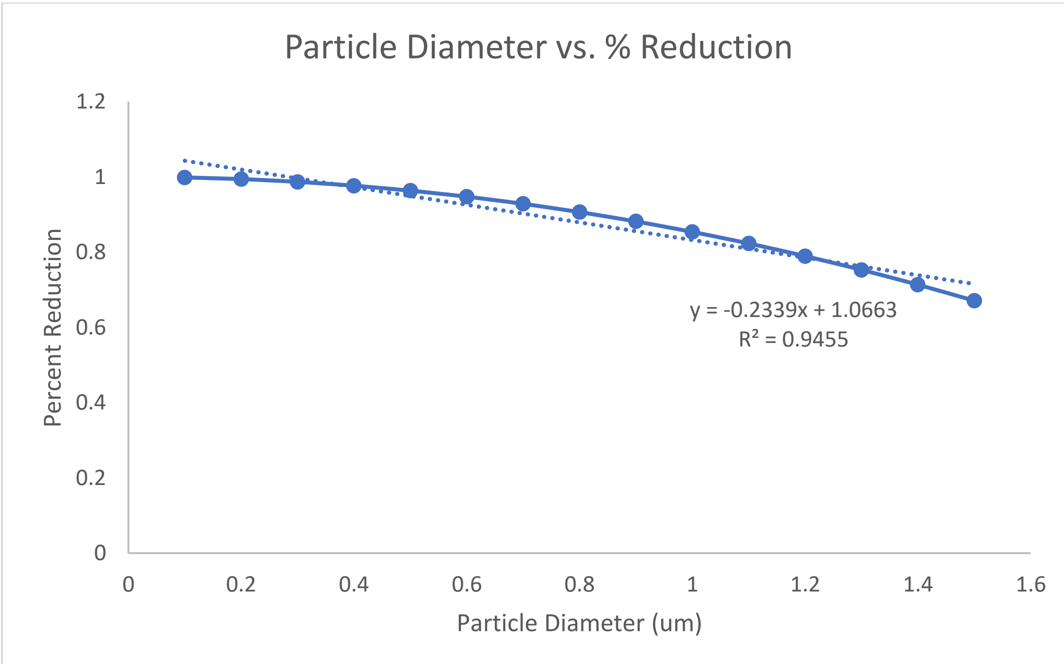

Figure 7: Graph of Particle Diameter versus Percent reduction for a 100% filled mine

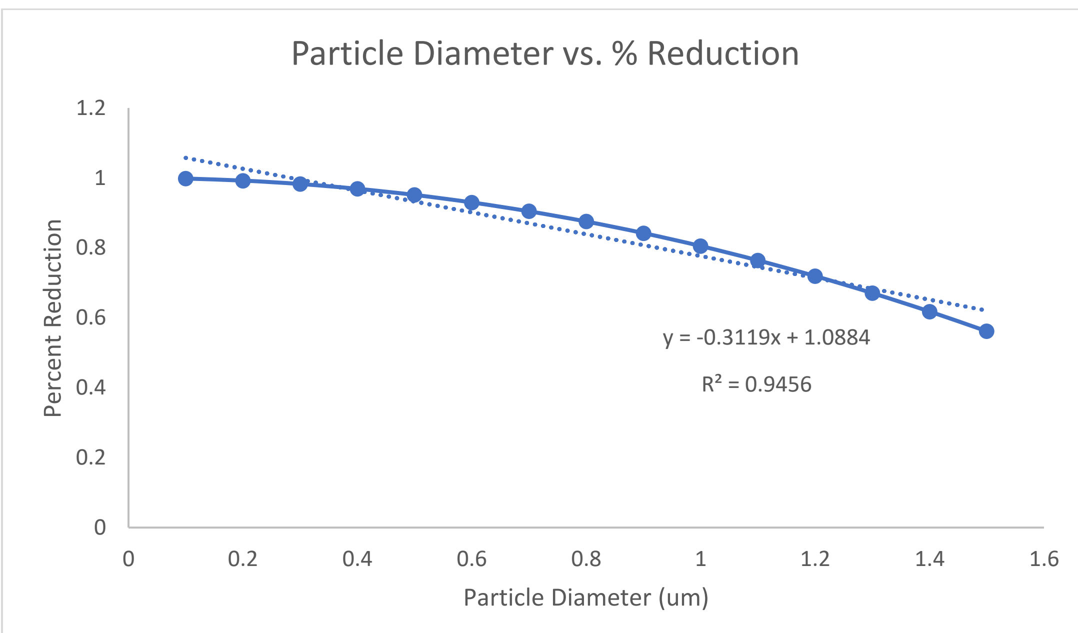

Figure 8: Graph of Particle Diameter versus Percent reduction for a 75% filled mine

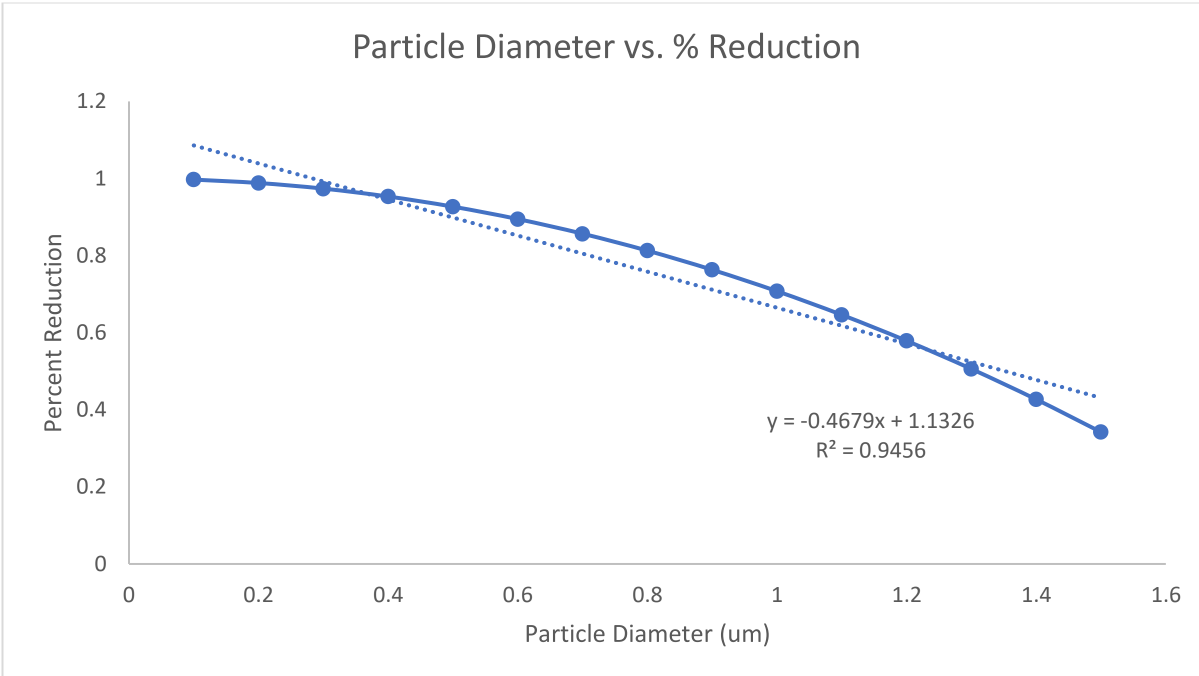

Figure 9: Graph of Particle Diameter versus Percent reduction for a 50% filled mine

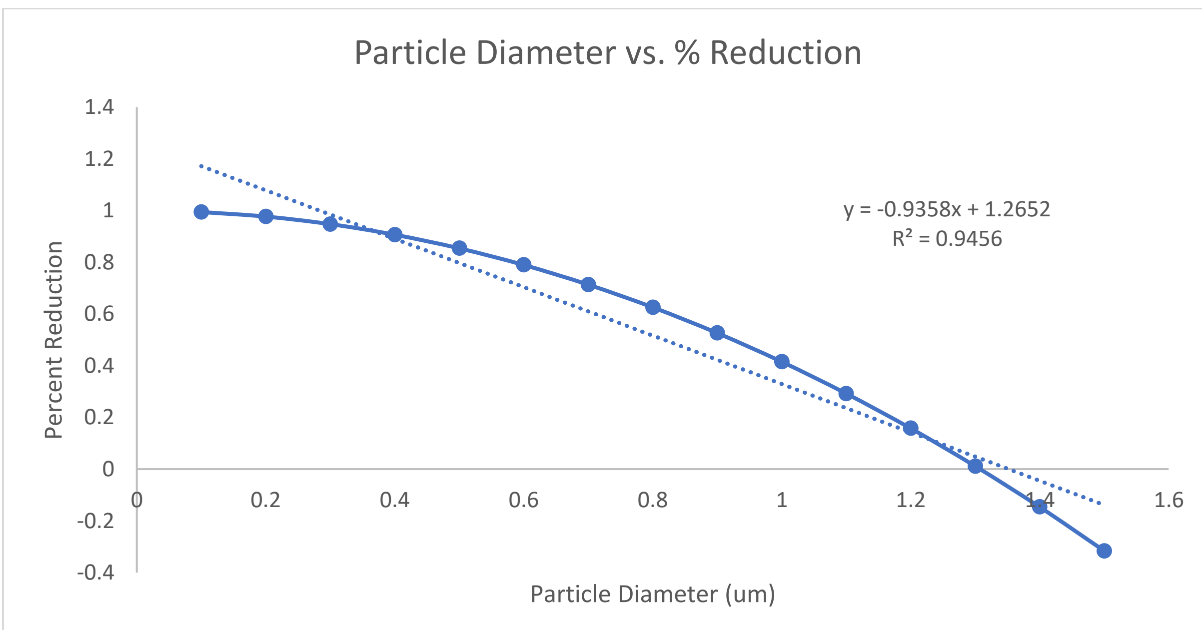

Figure 10: Graph of Particle Diameter versus Percent reduction for a 25% filled mine

Appendix D: Remediation Technologies

Exhibit 10-1
Remediation Technologies Matrix

Technology	Type	Media	Cost[2]	Effectiveness	Comments
Bioremediation	I/E	S	M-H	Innovative technology.	
Capping	C	S, sludges, wastes	L-H	Effective	
Capping (Erosion)	C	S, SW, A	L- M	Depends on site conditions, generally effective	O&M costs could be significant if the cap or cover is damaged.
Cement Walls	C	GW	M-H	Effective	
Chemical Treatment	C	SW, GW	M-H	Effective	O&M cost may be significant.
Decontamination	C	Structures	L-M	Depends on site conditions and contaminants	
Deed Restrictions	IC	Land	L	Depends on community acceptance	
Detention/ Sedimentation	C	SW	L-M	Effective	
Fencing	IC		L-M	Fencing can be effective at restricting access if the fences are maintained.	O&M costs can be significant, particularly for long stretches of fence.
Fines	IC	S, SW, GW, A	L	Depends on community acceptance	
Health Education Programs	IC	S,A,GW,S W	M-H	The effectiveness of any health education program depends on the community acceptance.	Needs local enforcement and support to be effective.
Interceptor Trenches	C	GW	L-H	Effective in capturing GW if the permeability is greater than native material	Significant O&M costs if the GW materials precipitate and reduce the permeability, requiring the media to be replaced or cleaned.
Interior Cleaning	IC	S, A	M-H	Can be very effective for removing the exposure to contaminants in interior dust.	Re-contamination is possible if sources have not been remediated.
Landfill Disposal	C	S, Solid Waste	M-H	Effective as long as the cap or liner are not breached.	May have significant O&M costs to maintain cap or treat leachate.

Figure 11: Table of Remediation technologies highlighting their cost and effectiveness

Exhibit 10-1 Remediation Technologies Matrix					
Technology	**Type**	**Media**	**Cost**[2]	**Effectiveness**	**Comments**
Limited Future Development	IC	Land	L	Depends on community acceptance	
Phytoextraction, Phytodegredation	I/E	S	L-M	Has been successful for some metals	May be considered innovative.
Programs to Encourage Interior Cleaning	IC	S, A	L	The effectiveness depends on community acceptance.	Some community members will not participate.
Pump and Treat	C	GW	M-H	Depends on site conditions and contaminant characteristics	
Regulatory Requirements	IC	S		The effectiveness depends on community acceptance.	Needs a source of funding to implement the permit issuing and tracking system.
Remining/ Reprocessing	I/E	S, Wastes	L-H	If all the material can be removed, this is a very effective technology; only a limited amount of material may, however, be available for remining.	Depends on the characteristics of the material to be reworked. Recovering salable metal may offset remediation costs. The time to reprocess large amounts of material could be significant and may not be acceptable.
Rhizofiltration	C	SW, GW	L-M	Innovative technology	
Run-on Controls	C	SW	L-M	Effective	
Sale of Useable Materials	C	feedstocks, wastes	L	Good	Limited to those materials that there is a market for.
Settling Basins	C	SW	L-H	Effective in removing suspended solids	May have significant O&M costs over the life of the dam.
Sheet Piling	C	GW	M-H	Effective	May have "leaks" in the wall
Signs	IC	S, SW, Waste Units	L	Signs have a very limited effectiveness	O&M costs can be significant if the signs keep "disappearing"
Slurry Walls	C	GW	M	Effective	May have "leaks" in the wall.
Soil Disposal	IC	S	M-H	The effectiveness depends on community acceptance.	Greatly depends on the handing and disposal requirements

Figure 12: Table of Remediation technologies highlighting their cost and effectiveness

Exhibit 10-1 Remediation Technologies Matrix					
Technology	**Type**	**Media**	**Cost**[2]	**Effectiveness**	**Comments**
Soil Flushing	C	S	M-H	Site conditions affect fluid's ability to mobilize contaminants	May be a concern with contamination of ground water.
Soil Washing	C	S	M-H	Site conditions affect fluid's ability to mobilize contaminants	
Solidification	C	S, sludges, wastes	M-H	Depends on the ability of the solid to break down over time.	
Solvent Extraction	C	S, wastes, sludges	L-H	Depends on the solutions' ability to extract contaminants	
Speed Limits	IC	A, S	L	The effectiveness depends on community acceptance.	Needs local enforcement and support to be effective.
Stabilization	C	S, sludges, wastes	M-H	Dependent on the nature of material to be stabilized.	
Stream Channel Erosion Control	C	SW	L-H	Effective	O&M costs can be significant.
Thermal Destruction	C	S, sludges, wastes	M-H	Poor for metals	Not common at most mining and mineral processing sites.
Thermal Desorption	C	S	M-H	Depends on site characteristics and contaminants	Not common at most mining and mineral processing sites.
Vapor Extraction	C	S	M-H	Depends on site characteristics and vapor phase contaminants	Not common at most mining and mineral processing sites.
Vehicle Limits	IC	S	L	The effectiveness depends on community acceptance.	Needs local enforcement and support to be effective.
Vitrification	I/E	S, Solid Waste	VH	Effective	Not common at mining and mineral processing sites.
Wind Breaks	C	S	L-M	Fair to good effectiveness	
Zoning	IC	S	L-M	The effectiveness depends on community acceptance.	Needs local enforcement and support to be effective.

Figure 13: Table of Remediation technologies highlighting their cost and effectiveness