Appendix A

Appendix A

**ADDITIONAL UNTREATED AND TREATED ACID MINE DRAINAGE
WASTEWATER CHARACTERIZATION DATA**

Table A-1 Additional Untreated Acid Mine Drainage Characteristics from *AMD143*

Table A-2 Additional Untreated Acid Mine Drainage Characteristics from *PADEPMDI*

Table A-3 Additional Treated Acid Mine Drainage Characteristics from *WVDMR*

Table A-4 Additional Treated Acid Mine Drainage Characteristics from *PADEPInspector*

Table A-1. Additional Untreated Acid Mine Drainage Characteristics from *AMD143*

Pollutant Parameter [a]	Minimum Recorded Value	Mean Recorded Value	Maximum Recorded Value
Antimony (µg/L)	<0.01	0.02	0.43
Arsenic (µg/L)	<0.03	4.67	64.00
Barium (µg/L)	2.00	15.40	39.00
Beryllium (µg/L)	0.05	3.97	52.00
Bismuth (µg/L)	<0.01	0.02	0.35
Boron (µg/L)	<1.00	61.29	260.00
Bromine (mg/L)	<0.003	0.06	0.60
Cadmium (µg/L)	<0.01	0.53	16.00
Cerium (µg/L)	0.01	21.81	370.00
Cesium (µg/L)	0.02	0.16	0.85
Chloride (mg/L)	0.10	21.32	460.00
Chromium (µg/L)	<0.50	3.09	72.00
Cobalt (µg/L)	0.27	130.63	3,100.00
Copper (µg/L)	0.40	11.07	190.00
Dysprosium (µg/L)	0.002	5.81	99.00
Erbium (µg/L)	0.003	3.01	58.00
Europium (µg/L)	0.002	1.27	22.00
Fluoride (mg/L)	<0.10	0.10	0.20
Gadolinium (µg/L)	0.005	6.16	110.00
Gallium (µg/L)	<0.01	0.31	7.30
Germanium (µg/L)	<0.01	0.09	0.57
Gold (µg/L)	0.0003	0.002	0.02
Hafnium (µg/L)	<0.002	0.17	7.10
Holmium (µg/L)	0.001	1.17	21.00
Indium (µg/L)	<0.001	0.01	0.34
Iodine (mg/L)	<0.001	0.01	0.10
Lanthanum (µg/L)	0.005	7.50	140.00
Lead (µg/L)	0.05	1.04	11.00
Lithium (µg/L)	11.00	82.77	390.00
Lutetium (µg/L)	<0.001	0.31	6.90
Mercury (µg/L)	<0.20	<0.20	<0.20
Molybdenum (µg/L)	0.06	0.28	2.60
Neodymium (µg/L)	0.006	15.17	260.00
Nickel (µg/L)	2.60	158.45	3,200.00
Niobium (µg/L)	<0.01	0.01	0.03
Nitrate (mg/L)	<0.03	0.03	0.15
Nitrite (mg/L)	<0.02	<0.02	<0.02
Osmium (µg/L)	<0.002	<0.002	<0.002
Palladium (µg/L)	<0.02	0.02	0.11
Platinum (µg/L)	<0.02	<0.02	<0.02

Table A-1. Additional Untreated Acid Mine Drainage Characteristics from *AMD143*

Pollutant Parameter [a]	Minimum Recorded Value	Mean Recorded Value	Maximum Recorded Value
Potassium (mg/L)	0.50	3.06	12.00
Praseodymium (µg/L)	0.002	3.26	54.00
Rhenium (µg/L)	<0.001	0.002	0.01
Rubidium (µg/L)	1.00	7.62	28.00
Ruthenium (µg/L)	<0.02	0.02	0.17
Samarium (µg/L)	<0.005	4.73	79.00
Scandium (µg/L)	1.00	7.60	36.00
Selenium (µg/L)	<0.2	0.93	7.60
Silica (mg/L)	5.80	20.75	67.00
Silver (µg/L)	0.01	0.20	0.50
Sodium (mg/L)	0.69	53.11	500.00
Strontium (µg/L)	27.00	924.41	3,600.00
Tantalum (µg/L)	<0.01	0.01	0.11
Tellurium (µg/L)	<0.20	0.20	0.40
Terbium (µg/L)	0.001	1.08	18.00
Thallium (µg/L)	0.006	0.14	1.50
Thorium (µg/L)	<0.003	0.50	24.00
Thulium (µg/L)	<0.001	0.40	8.30
Tin (µg/L)	<0.10	0.10	0.20
Titanium (µg/L)	0.65	6.20	28.00
Tungsten (µg/L)	<0.02	0.08	0.52
Uranium (µg/L)	<0.006	1.19	100.00
Vanadium (µg/L)	0.006	0.95	18.00
Ytterbium (µg/L)	0.002	2.21	48.00
Yttrium (µg/L)	0.11	28.63	530.00
Zinc (µg/L)	0.60	341.55	10,000.00
Zirconium (µg/L)	<0.03	0.07	0.84

Source: *AMD143*.

a – All 143 outfalls were sampled for each pollutant. Therefore, the number of permits for each pollutant is 143.

< – Indicates the sample result was less than the detection limit.

Table A-2. Additional Untreated Acid Mine Drainage Characteristics from *PADEPMDI*

Pollutant Parameter	Number of Permits [a]	Minimum Recorded Value	Mean Recorded Value	Maximum Recorded Value
Antimony (µg/L)	4	2.00	3.25	5.00
Boron (mg/L) [b]	6	200.00	200.00	200.00
Carbon (mg/L)	4	1.00	32.25	2.00
Chloride (mg/L)	87	1.00	27.10	430.00
Cobalt Compounds (µg/L)	4	50.00	453.75	1,370.00
Dissolved Solids (mg/L)	81	112.00	2,275.85	5,463.00
Fluoride (mg/L)	4	1.00	1.50	2.00
Hot Acidity (mg/L)	573	-198.37	324.41	26,961.33
Molybdenum (µg/L) [b]	4	70.00	70.00	70.00
Nitrate (mg/L)	5	1.00	2.40	7.00
Nitrogen (mg/L) [b]	3	1.00	1.00	1.00
Potassium (mg/L)	71	1.00	6.11	51.00
Selenium (µg/L)	21	7.00	11.57	24.00
Silica (mg/L)	6	17.00	31.83	51.00
Silver (µg/L)	6	10.00	12.67	18.00
Sodium (mg/L)	494	2.00	46.66	508.00
Strontium (µg/L)	1	1,640.00	1,640.00	1,640.00
Titanium (µg/L)	3	15.00	17.00	18.00
Total Arsenic (µg/L)	20	4.00	6.20	13.00
Total Barium (µg/L)	19	9.00	30.16	202.00
Total Cadmium (µg/L)	20	1.00	9.15	20.00
Total Chromium (µg/L)	20	35.00	46.40	50.00
Total Copper (µg/L)	17	9.00	25.12	145.00
Total Lead (µg/L)	20	1.00	5.55	25.00
Total Mercury (µg/L) [b]	20	1.00	1.00	1.00
Total Nickel (µg/L)	20	50.00	858.00	2,080.00
Total Zinc (µg/L)	78	10.00	1,300.71	7,265.00

Source: *PADEPMDI*.
a – Excludes recorded values of zero, except for hot acidity.
b – Below detection indicators are not reported in the *PADEPMDI* database. EPA believes these samples are the detection limit due to all of the samples having the same value.

Table A-3. Additional Treated Acid Mine Drainage Characteristics from *WVDMR*

Pollutant Parameter	Number of Permits [a]	Minimum Recorded Value	Mean Recorded Value	Maximum Recorded Value
Ammonia, as Nitrogen (mg/L)	93	0.02	54.59	373.12
Ammonia, Unionized (mg/L)	85	0.0002	5,491.05	167,329.17
Barium (mg/L)	67	0.0005	3.33	31.51
Biological Oxygen Demand (mg/L)	5	<4.00	20.15	43.87
Chemical Oxygen Demand (mg/L)	2	1.00	7.00	13.00
Chloride (mg/L)	64	2.74	124.85	1,793.33
Dissolved Aluminum (mg/L)	995	0.006	0.20	20.14
Dissolved Copper (mg/L)	1	0.01	0.01	0.01
Dissolved Lead (mg/L)	7	0.001	0.02	0.04
Dissolved Zinc (mg/L)	3	0.006	0.01	0.02
Hexavalent Chromium (mg/L)	3	0.000005	0.00002	0.00002
Nitrogen, as Ammonia (mg/L)	1	1.00	1.00	1.00
Settleable Solids (mL/L)	241	<0.01	1.29	225.05
Total Antimony (mg/L)	5	0.0002	0.009	0.02
Total Recoverable Arsenic (mg/L)	69	0.000001	0.20	6.50
Total Recoverable Beryllium (mg/L)	3	0.001	0.002	0.002
Total Boron (mg/L)	4	0.00009	0.01	0.05
Total Cadmium (mg/L)	16	0.000005	0.14	2.30
Total Chromium (mg/L)	5	0.0002	1.13	5.60
Total Copper (mg/L)	21	<0.00002	0.97	11.81
Total Cyanide (mg/L)	2	0.002	0.002	0.002
Total Dissolved Solids (mg/L)	25	63.07	1,085.03	4,432.50
Total Hot Acidity (mg/L)	207	-388.48	27.50	2,715.27
Total Kjeldahl Nitrogen (mg/L)	1	4.16	4.16	4.16
Total Lead (mg/L)	67	0.000001	0.28	5.84
Dissolved Manganese (mg/L)	1	2.16	2.16	2.16
Total Recoverable Mercury (mg/L)	63	0.0000001	0.21	5.00
Total Nickel (mg/L)	53	0.000003	3.66	101.34
Total Recoverable Selenium (mg/L)	251	0.000002	0.43	19.69
Total Silver (mg/L)	8	0.00002	0.57	4.50
Total Recoverable Thallium (mg/L)	2	0.0001	0.004	0.007
Total Vanadium (mg/L)	1	0.001	0.001	0.001
Total Zinc (mg/L)	28	0.00004	0.09	1.11

Source: *WVDMR*.

a – Excludes recorded values of zero, except for hot acidity.

< – Indicates the sample result was less than the detection limit.

Table A-4. Additional Treated Acid Mine Drainage Characteristics from *PADEPInspector*

Pollutant Parameter	Number of Permits [a]	Minimum Recorded Value	Average Recorded Value	Maximum Recorded Value
Dissolved Aluminum (mg/L)	2	<0.20	0.66	1.12
Dissolved Arsenic (mg/L)	2	0.003	0.008	0.01
Dissolved Cadmium (mg/L)	2	<0.001	<0.001	0.001
Dissolved Calcium (mg/L)	2	315.83	336.67	357.50
Dissolved Chromium (mg/L)	2	<0.05	<0.05	<0.05
Dissolved Copper (mg/L)	2	<0.01	<0.01	<0.01
Dissolved Lead (mg/L)	2	<0.001	0.003	0.004
Dissolved Magnesium (mg/L)	2	175.50	194.25	213.00
Dissolved Manganese (mg/L)	2	5.78	10.01	14.25
Dissolved Mercury (mg/L)	2	0.001	0.001	0.001
Dissolved Nickel (mg/L)	2	0.05	0.13	0.20
Dissolved Potassium (mg/L)	2	6.64	19.82	33.00
Dissolved Selenium (mg/L)	2	<0.007	0.02	0.03
Dissolved Sodium (mg/L)	2	17.63	21.80	25.97
Dissolved Zinc (mg/L)	2	<0.01	0.11	0.21
Hot Acidity (mg/L)	321	-1,522.00	-40.71	8,042.64
Nitrate, as N (mg/L)	1	0.37	0.37	0.37
Total Arsenic (mg/L)	2	<0.004	0.35	0.70
Total Cadmium (mg/L)	2	0.01	0.01	0.01
Total Calcium (mg/L)	8	16.20	134.78	322.50
Total Chloride (mg/L)	5	3.28	62.12	256.00
Total Chromium (mg/L)	2	<0.05	0.13	0.21
Total Copper (mg/L)	2	<0.01	0.36	0.71
Total Dissolved Solids (mg/L)	23	454.32	2,170.00	16,513.33
Total Lead (mg/L)	2	0.002	0.004	0.01
Total Mercury (mg/L)	2	0.001	0.001	0.001
Total Nickel (mg/L)	2	0.05	0.52	0.98
Total Potassium (mg/L)	2	19.92	32.76	45.60
Total Selenium (mg/L)	2	0.01	0.04	0.06
Total Sodium (mg/L)	13	5.37	278.93	1,360.00
Total Zinc (mg/L)	2	0.63	1.81	2.99

Source: *PADEPInspector*.
a – Excludes recorded values of zero, except for hot acidity.
< – Indicates the sample result was less than the detection limit.

Appendix B

DRAFT ACID MINE DRAINAGE TREATMENT COST MODULE: CHEMICAL PRECIPITATION USING CAUSTIC SODA

Draft Acid Mine Drainage Treatment Cost Module:
Chemical Precipitation Using Caustic Soda
August 16, 2007

Disclaimer: This is a <u>draft</u> module for a cost estimation tool. EPA developed this module for the Detailed Study of the Coal Mining Point Source Category (40 CFR Part 434) to estimate the cost difference between treating acid mine drainage (AMD) using caustic soda chemical precipitation over a range of flows:

- To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
- To meet only the TSS, pH, and iron limitations in 40 CFR Part 434.

The costs are based on calculations and default values provided in the *AMDTreat*® software that was developed cooperatively by the Pennsylvania Department of Environmental Protection (PA DEP), West Virginia Department of Environmental Protection (WV DEP), and the U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE). The default values from *AMDTreat*® that are used in the caustic soda chemical precipitation module are presented in Attachment A.

OSMRE reviews and updates the treatment costs roughly annually. The most recent version of *AMDTreat*®, version 4.1, expresses costs in 2006 dollars. *AMDTreat*® *v.4.1* has not been peer reviewed (OSMRE, 2007).

1.0 MODULE METHODOLOGY

This module estimates the costs associated with installing and operating a caustic soda (NaOH) chemical precipitation system for treating AMD. Chemical precipitation using caustic has been used widely to neutralize acidity and precipitate metal ions in AMD since the passage of the Surface Mining, Control, and Reclamation Act of 1977 (SMCRA) and the Coal Mining Effluent Guidelines and Standards (40 CFR Part 434). EPA is estimating the cost difference between using chemical precipitation to achieve two different effluent scenarios:

1. To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
2. To meet only the pH, solids, and iron limitations of 40 CFR Part 434.

40 CFR Part 434 defines AMD as mine drainage that, before treatment, either has a pH of less than 6.0 or a total iron concentration equal to or greater than 10 mg/L. The limitations for AMD are in 40 CFR Part 434 Subpart C, shown in Table 1-1 (BAT) and Table 1-2 (NSPS). The best available control technology (BAT) limitations apply to coal mines that were constructed prior to May 4, 1984. The new source performance standards (NSPS) limitations apply to coal mines that were constructed after May 4, 1984. EPA assumes that the majority of the coal mines are required to meet NSPS limitations and will use the NSPS limitations presented in Table 1-2 for the effluent scenarios.

Table 1-1. BAT Effluent Guidelines for Coal Mining Part 434, Subpart C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.5	7.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.
[a]Subpart C – Acid or Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Industry.

Table 1-2. NSPS Effluent Guidelines for Coal Mining Part 434, Subparts C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.
[a]Subpart C – Acid or Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Industry.

Under the first effluent scenario, EPA estimates the costs to remove pollutants to meet all the NSPS limitations in Table 1-2. Under the second effluent scenario, EPA estimates the costs to remove all pollutants except manganese to the NSPS limitations level required by 40 CFR Part 434 presented in Table 1-2.

2.0   PROCESS DESCRIPTION

Chemical precipitation is widely used in the coal mining industry to meet NPDES permit limitations. This section describes chemical precipitation in general (Section 2.1) and how it specifically applies to AMD (Section 2.2).

2.1   Chemical Precipitation

Chemical precipitation involves removing metallic contaminants from aqueous solutions by converting soluble heavy metals to insoluble salts. The precipitated solids are then removed from solution by flocculation followed by sedimentation and/or filtration. Precipitation is caused by the addition of chemical reagents that increase the pH of the water to the minimum solubility of the metal. The standard reagents include the following (EPA, 2000):

- Lime (calcium hydroxide);
- Caustic (sodium hydroxide);

- Magnesium hydroxide;
- Soda ash (sodium carbonate);
- Trisodium phosphate;
- Sodium sulfide; and
- Ferrous sulfide.

These reagents precipitate metals as hydroxides, carbonates, phosphates, or sulfides. The precipitated metals form sludge. Over time, the accumulated sludge must be removed from the treatment system.
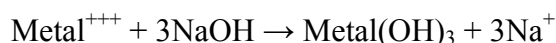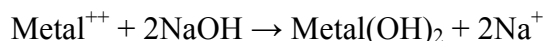
2.2 Chemical Precipitation of AMD

The majority of coal mines treating AMD use lime or caustic for precipitation. Metals commonly targeted for removal from solution by precipitation include iron, manganese, and aluminum.

Figure 2-1 shows an example chemical precipitation process:

- The AMD is aerated, often by gravity flow and sprays, to increase the dissolved oxygen in the discharge. The increased dissolved oxygen allows some metals to oxidize and form metal hydroxides, such as ferric hydroxide ($Fe(OH)3$).
- The first settling pond removes the majority of the metal hydroxides that formed due to aeration.
- A chemical precipitant is added in a channel or pond, where the remaining dissolved metals, such as manganese and magnesium, are oxidized to an insoluble form.
- The remaining settling ponds remove the suspended insoluble metal hydroxides.

Hydroxide precipitation normally involves using lime ($Ca(OH)_2$) or caustic soda ($NaOH$) as a precipitant to remove metals as insoluble metal hydroxides. The reaction is illustrated by the following equations for precipitation of divalent and trivalent metals using caustic soda:

$$Metal^{++} + 2NaOH \rightarrow Metal(OH)_2 + 2Na^+$$

$$Metal^{+++} + 3NaOH \rightarrow Metal(OH)_3 + 3Na^+$$

The effluent metals concentration attained by hydroxide precipitation depends on the metals present and reaction conditions. Many scientists have studied metals removal from AMD, particularly the difficulty of removing manganese. Two studies in particular address EPA's question of the incremental cost to remove manganese:

- Kirby and Cravotta: Net Alkalinity and Net Acidity 1: Theoretical Considerations (Kirby, 2005a) and Net Alkalinity and Net Acidity 2: Practical Considerations (Kirby, 2005b). Attachment B contains these articles.
- Means and Hilton: Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage (Means, 2004). Attachment C contains this article.

While scientists have found that iron will precipitate quickly at a pH near 7, manganese precipitates quickly only when the pH is raised to 9 or 10 (Means, 2004). Figure 2-2 illustrates the solubility curves from research performed by Dr. Chuck Cravotta, U.S.G.S., for metals commonly in AMD, showing solubilities relative to pH.
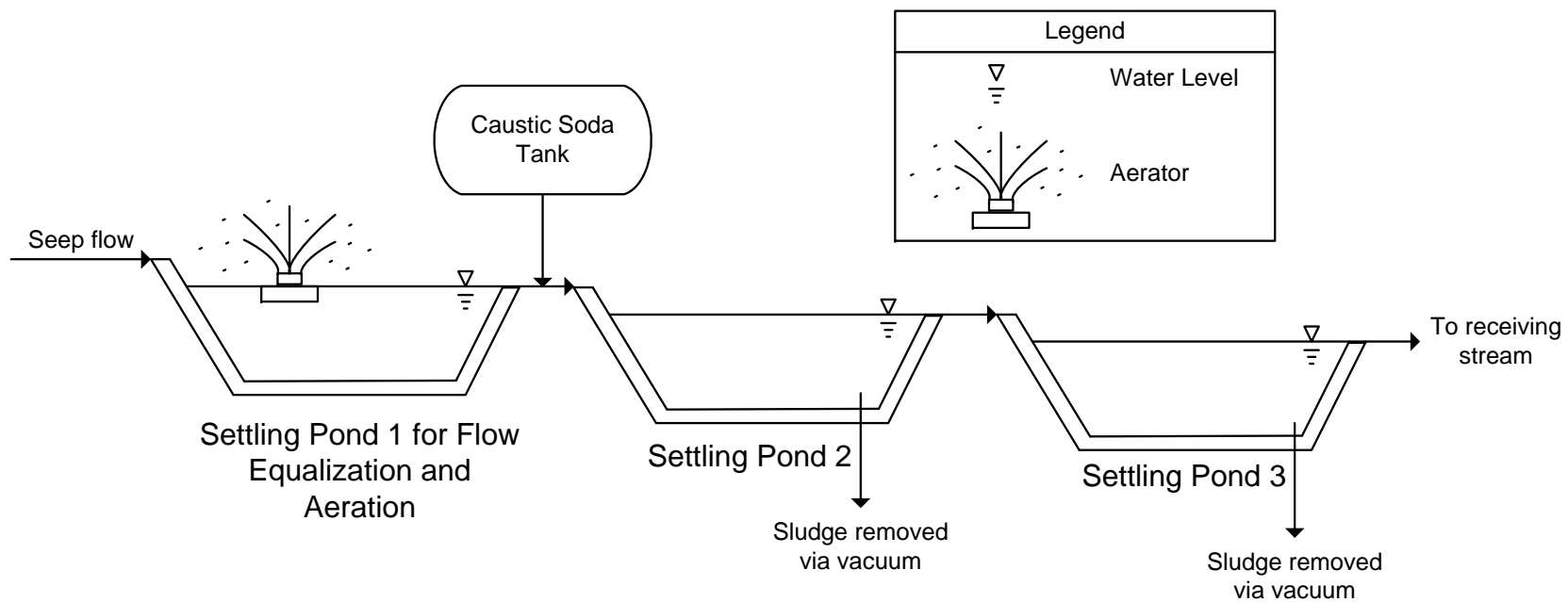
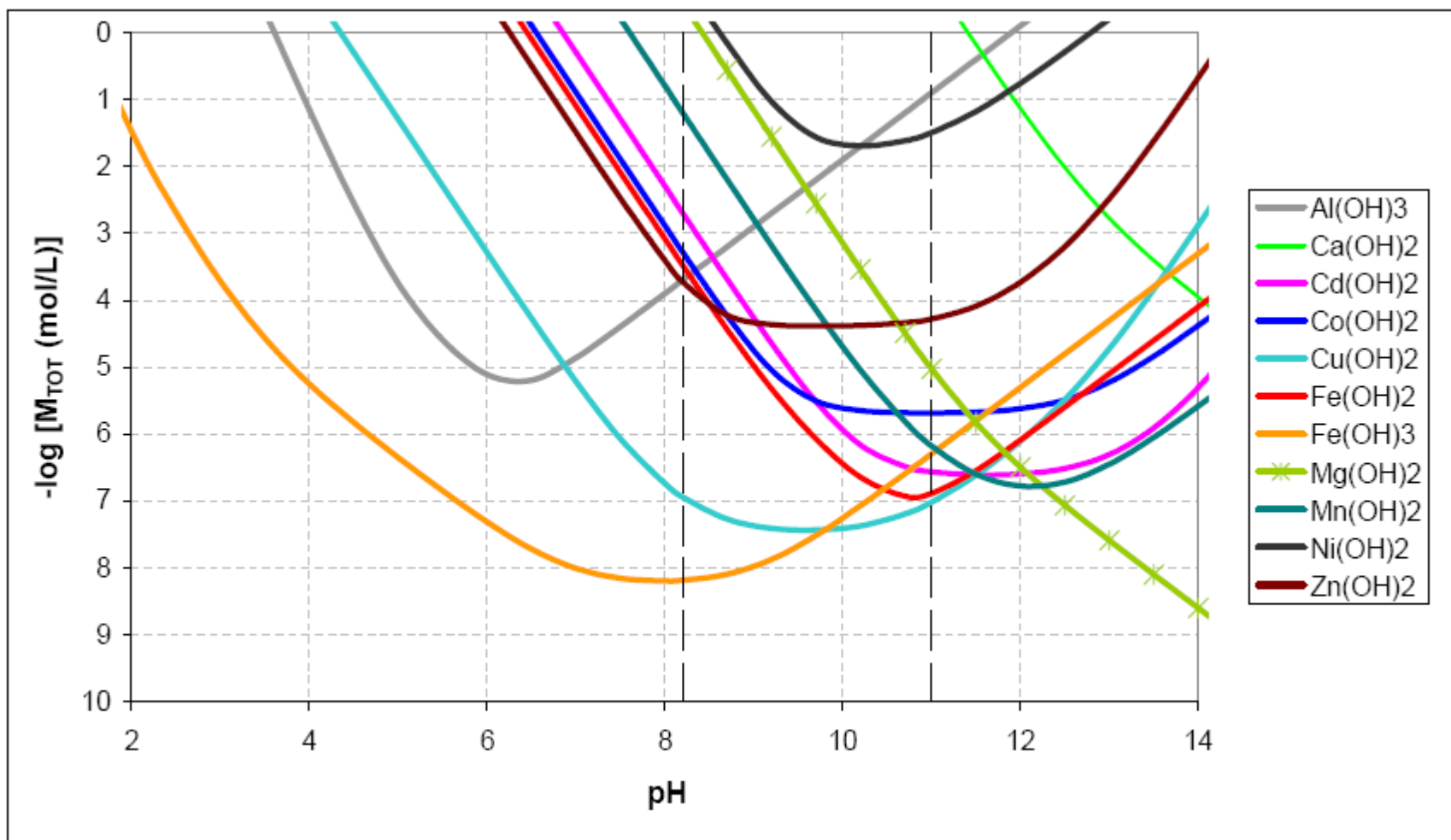**Figure 2-1. Example AMD Chemical Precipitation Treatment System using Caustic Soda**

Figure 2-2. Comparison of Metal Hydroxide Solubilities for Constituents Commonly Found in Acidic Mine Drainage (Means, 2004)

3.0   DESIGN CONSIDERATIONS

This cost module considers the costs required for chemical precipitation using caustic soda (NaOH). EPA is estimating the cost of treating AMD with chemical precipitation using hydrated lime and with a limestone bed in separate cost modules (see "Draft Acid Mine Drainage Treatment Cost Module: Chemical Precipitation Using Hydrated Lime" and "Draft Acid Mine Drainage Treatment Cost Module: Limestone Bed" both dated August 2007 (see Appendices D and E of the Coal Mining Detailed Study Report)). EPA considered the amount of caustic soda required to adjust pH to a given level, the amount of sludge generated and the cost of its removal, and the required operating labor.

EPA assumes that annual costs for electricity and land requirements are approximately equal under both effluent scenarios. For this reason, EPA did not consider the cost of obtaining or leasing land for the treatment system or other capital equipment costs or electricity needs in its estimate of annual costs.

4.0   COST MODULE CALCULATIONS

EPA is estimating costs to treat AMD with chemical precipitation using caustic soda to achieve two different effluent scenarios:

1.   To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
2.   To meet only the TSS, pH, and iron limitations of 40 CFR Part 434.

Table 4-1 presents the limits for each of the effluent scenarios. The difference between the effluent scenarios is that effluent scenario 1 meets the current manganese limits while effluent scenario 2 does not incorporate any change in manganese concentration. For calculation purposes, only the 30-day limit is considered, because it is lower than the daily maximum limit.

Table 4-1. Effluent Discharge Limitations for Effluent Scenarios

Parameter	Effluent Scenario 1		Effluent Scenario 2	
	NSPS 30-Day Average (mg/L)	NSPS Daily Maximum (mg/L)	NSPS 30-day Average (mg/L)	NSPS Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70	35	70
pH	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0	3.0	6.0
Manganese, Total	2.0	4.0	NA	NA

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.

The first effluent scenario will be achieved by treating the AMD to pH 10 using caustic soda, based on the solubility of the metals. EPA assumes that at pH 10 the effluent will result in the following characteristics based on the metals solubilities from Figure 2-2 (Means, 2004):[1]

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

Although the caustic soda addition results in pH 10 for effluent scenario 1, after the settling ponds where the metal hydroxides are removed the pH will decrease and meet the limitation in Table 4-1 prior to discharge.

The second effluent scenario will be achieved by treating the AMD to pH 8.3 using caustic soda. EPA assumes that at pH 8.3 the effluent will result in the following characteristics based on the metals solubilities from Figure 2-2 (Means, 2004):[2]

- Iron at 3.0 mg/L;
- A 10 percent reduction in manganese from untreated;
- A 99 percent reduction in aluminum from untreated; and
- No reduction in magnesium from untreated.

Additionally, the final pH will remain in the range of 6 to 9 to meet the limitation.

For both effluent scenarios the cost module includes the following items:

- Annual Costs (Section 4.1) including;
  — Chemicals cost (Section 4.1.1);
  — Sludge removal cost (Section 4.1.2);
  — Sampling cost (Section 4.1.3); and
  — Maintenance cost (Section 4.1.4) that includes maintenance labor and the annual cost for replacement of chemical storage system every 20 years.
- Capital Costs (Section 4.2) that includes chemicals storage cost (Section 4.2.1).

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[1] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.

[2] Ibid.

The sampling cost and maintenance labor cost will be the same for each effluent scenario because these portions of the cost module do not depend on effluent water characteristics. Therefore, the sampling cost and maintenance cost for each effluent scenario will off-set when the total costs are compared. However, these costs are included for comparison to other costing modules in EPA's Detailed Study of the Coal Mining Industry.

4.1   Annual Costs

The following sections describe the calculation of annual costs.

4.1.1   Chemical Cost

Under the first effluent scenario, EPA is estimating the cost of caustic soda to reach approximately pH 10. EPA assumes that at pH 10 the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) and manganese (2 mg/L 30-day average) limitations based on the solubility of these metals, presented in Figure 2-2 (Means, 2004). Under the second effluent scenario, EPA is estimating the cost of caustic soda to reach approximately pH 8.3. EPA assumes that at pH 8.3 the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) limitation but will not meet the manganese (2 mg/L 30-day average) limitation (Means, 2004).[3]

The amount of caustic soda required annually depends on three things:

1.   Net acidity;
2.   Discharge flow rate; and
3.   The additional acidity required to increase the pH to the desired level.

The net acidity is estimated based on pH, metals concentrations (specifically ferrous and ferric iron, manganese, and aluminum), additional acidity liberated to achieve pH 10, and alkalinity. Equation 1 can be used to calculate the net acidity.

$$\text{Net Acidity} = 50 * \left\{ (1000 * 10^{-pH}) + \frac{2 * Fe^{2+} + 3 * Fe^{3+}}{55.842} + \frac{2 * Mn}{54.93807} + \frac{3 * Al}{26.9815386} \right\} * \text{Acidity Multiplier} - \text{Alkalinity} \qquad (1)$$

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[3] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumptions that 1) a multiplier of 4 accounts for the additional acidity liberated when raising pH to 10 to settle manganese and 2) that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. 1) Mine drainage chemistry is complex and variable. In some AMD, as demonstrated in *Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004), there may be little additional acidity liberated when titrating pH to 10. For AMD with these characteristics, the multiplier of 4 overestimates the amount of treatment chemical required to adjust pH for manganese treatment. 2) Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.

where:

- Acidity Multiplier. A factor accounting for additional acidity liberated to achieve pH 10;
- Net acidity. Laboratory-measured acidity; and
- Alkalinity. Laboratory-measured alkalinity.

The acidity multiplier is derived from the Means and Hilton article entitled *Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage*, in Attachment C. The scientists found that the Standard Method (SM) 2310 for hot acidity is often not a valid expression of acidity for waters with pH's greater than 8.2. The article concludes that when adding caustic to adjust pH for manganese precipitation (i.e., to increase the pH to 10), plant operators must consider the amount of caustic consumed by magnesium and other ions. The amount of caustic consumed by magnesium and other ions at pH's above 10 is not accounted for by SM 2310.

As a result, EPA used data from the Means and Hilton article to estimate the additional caustic needed when adjusting pH above 8.3. Means and Hilton provide data for four different discharges of AMD (Means, 2004). EPA selected the "worst case scenario," or the data for the AMD requiring the greatest additional caustic to increase the pH to 10, for manganese removal. The data demonstrate that to adjust pH from 8.3 to 10, roughly three times the amount of caustic is necessary, and the acidity multiplier is 4.

The amount of caustic soda required to neutralize the net acidity is based on the discharge flow rate, mixing efficiency, and caustic soda purity. Equation 2 can be used to calculate the amount of caustic soda required to neutralize the net acidity to achieve a specific pH (pH 10 for effluent scenario 1 and pH 8.3 for effluent scenario 2).

$$\text{NaOH}_{req} = \text{Net Acidity} * \frac{2 \text{ mol NaOH}}{1 \text{ mol CaCO}_3} * \frac{\text{MW}_{\text{NaOH}}}{\text{MW}_{\text{CaCO3}}} * \frac{\text{Flow}}{\text{Density}_{\text{NaOH}}} * \frac{100}{\text{Purity}} * \frac{100}{\text{Efficiency}} * \text{CF}_{weight} * \text{CF}_{time} * \text{CF}_{volume} \quad (2)$$

Equation 3 can be used to calculate the annual cost of caustic soda required to neutralize the net acidity.

$$\text{Annual Chemical Cost} = \text{NaOH}_{req} * \text{Caustic Soda Cost} \quad (3)$$

Table 4-2 describes the variables in the chemical cost section of the caustic soda cost module shown in equations 1, 2, and 3 and provides the values used in the equations for each effluent scenario.

Table 4-2. Chemical Cost Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Acidity Multiplier	None	Multiplier of additional acidity liberated when increasing the pH from 8.3 to 10	4	Means, 2004	0	Kirby, 2005
Alkalinity	mg CaCO$_3$/L	Alkalinity in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Annual Chemical Cost	$/yr	Annual cost of caustic soda	NA	Calculated in Equation 3	NA	Calculated in Equation 3
Caustic Soda Cost	$/gal	Cost of caustic soda	$ 0.70/gal	*AMDTreat® v.4.1*	$ 0.70/gal	*AMDTreat® v.4.1*
CF$_{time}$	min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
CF$_{volume}$	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
CF$_{weight}$	lb/mg	Conversion factor for converting pounds to milligrams	2.205 x 10^{-6} lb/mg	Constant	2.205 x 10^{-6} lb/mg	Constant
Density$_{NaOH}$	lb/gal	Density of 99 % purity sodium hydroxide solution	0.49 lb/gal	*AMDTreat® v.4.1*	0.49 lb/gal	*AMDTreat® v.4.1*
Efficiency	%	Mixing efficiency of caustic soda with discharge	100 %	*AMDTreat® v.4.1*	100 %	*AMDTreat® v.4.1*
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Flow	Gpm	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
MW$_{CaCO3}$	g/mol	Molecular weight for caustic soda	100.0869 g/mol	Constant	100.0869 g/mol	Constant
MW$_{NaOH}$	g/mol	Molecular weight for sodium hydroxide	39.9972 g/mol	Constant	39.9972 g/mol	Constant
NaOH$_{req}$	gal/yr	Amount of 99 % caustic soda solution required to neutralize the net acidity	NA	Calculated in Equation 2	NA	Calculated in Equation 2

Table 4-2. Chemical Cost Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Net Acidity	mg CaCO$_3$/L	Discharge net acidity	NA	Calculated in Equation 1	NA	Calculated in Equation 1
pH	standard units	Untreated discharge pH	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Purity	%	Purity of caustic soda	99 %	*AMDTreat® v.4.1*	99 %	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.2 Sludge Removal Cost

The sludge generated annually depends on the water chemistry, such as final pH and ion concentrations, and settling pond retention time. EPA assumes that when the discharge reaches pH 10 for effluent scenario 1, the following effluent quality will be achieved based on metal solubilities (see Figure 2-2) (Means, 2004):[4]

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

EPA assumes that when the discharge reaches pH 8.3 for effluent scenario 2, the following effluent quality will be achieved based on metals solubilities (see Figure 2-2) (Means, 2004):[5]

- Iron at 3.0 mg/L;
- A 10 percent reduction in manganese from untreated;
- A 99 percent reduction in aluminum from untreated; and
- No reduction in magnesium from untreated.

This cost module does not include the amount of sludge generated from other insoluble metal hydroxides; however, it over estimates sludge resulting from the iron, aluminum, manganese, and magnesium.

Equations 4, 5, 6, and 7 calculate the amount of sludge generated from aluminum, iron, manganese, and manganese, respectively. Equation 8 calculates the annual sludge removal cost.

$$\text{Sludge}_{Al} = (Al * Al_{reduction}) * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \qquad (4)$$

$$\text{Sludge}_{Fe} = \{(Fe^{3+} + Fe^{2+}) - Fe_{limit}\} * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \qquad (5)$$

$$\text{Sludge}_{Mn} = (Mn - Mn_{limit}) * Mn_{reduction} * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \qquad (6)$$

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[4] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron. The costs estimated for sludge removal represent 4 percent of the total annualized cost, at a maximum.
[5] Ibid.

$$\text{Sludge}_{Mg} = (Mg * Mg_{reduction}) * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \ Solids} \tag{7}$$

$$\text{Annual Sludge Cost} = \{Sludge_{Al} + Sludge_{Fe} + Sludge_{Mn} + Sludge_{Mg}\} * Removal\ Cost \tag{8}$$

Table 4-3 describes the variables in the sludge removal cost section of the caustic soda cost module shown in equations 4, 5, 6, 7, and 8 and provides the values used in the equations for each effluent scenario.

Table 4-3. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
% Solids	%	Ratio of the weight of solids to the weight of water	5 %	*AMDTreat® v.4.1*	5 %	*AMDTreat® v.4.1*
Al	mg/L	Aluminum concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$Al_{reduction}$	%	Percent reduction of aluminum from untreated to final effluent	99 %	Solubility Curve (Means, 2004)	99 %	Solubility Curve (Means, 2004)
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 8	NA	Calculated in Equation 8
CF_{time}	Min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
CF_{volume}	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
CF_{weight}	mg/lb	Conversion factor for converting milligrams to pounds	454,00 mg/lb	Constant	454,000 mg/lb	Constant
$Density_{sludge}$	lb/gal	Density of solids and water in sludge	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe_{limit}	mg/L	Effluent limit for iron	3.0 mg/L	40 CFR Part 434	3.0 mg/L	40 CFR Part 434
Flow	Gpm	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mg	mg/L	Magnesium concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$Mg_{reduction}$	%	Percent reduction of magnesium from untreated to final effluent	10 %	Solubility Curve (Means, 2004)	0 %	Solubility Curve (Means, 2004)
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics

Table 4-3. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Mn_{limit}	mg/L	Effluent limit for manganese	2.0 mg/L	40 CFR Part 434	0	Effluent value will be estimated based on performance data received from coal mines with chemical precipitation.
$Mn_{reduction}$	%	Percent reduction of manganese from untreated to final effluent	100 %	EPA calculates final manganese concentration using limit rather than percent reduction	10 %	Solubility Curve (Means, 2004)
Removal Cost	$/gal	Cost of removing sludge	$ 0.06/gal	*AMDTreat® v.4.1*	$ 0.06/gal	*AMDTreat® v.4.1*
$Sludge_{Al}$	gal/yr	Amount of sludge generated from the precipitation of aluminum	NA	Calculated in Equation 4	NA	Calculated in Equation 4
$Sludge_{Fe}$	gal/yr	Amount of sludge generated from the precipitation of iron	NA	Calculated in Equation 5	NA	Calculated in Equation 5
$Sludge_{Mg}$	gal/yr	Amount of sludge generated from the precipitation of magnesium	NA	Calculated in Equation 7	NA	Calculated in Equation 7
$Sludge_{Mn}$	gal/yr	Amount of sludge generated from the precipitation of manganese	NA	Calculated in Equation 6	NA	Calculated in Equation 6

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.3 Sampling Cost

The annual sampling cost includes the labor for collecting the samples and the sampling lab analysis costs. This cost module assumes that the number of samples required yearly is independent of the flow, net acidity, raw AMD metals concentrations, or treatment technology. Based on conversations with coal mine wastewater treatment operators, sampling is only conducted to meet the NPDES permit requirements (Wolford, 2007b; Wolford, 2007c). The sampling costs for both effluent scenarios are the same because sampling requirements are independent of effluent quality. EPA included the sampling costs anyway.

Equations 9, 10, 11, and 12 can be used to calculate the annual sampling cost assuming the NPDES permits require bi-monthly sampling.

$$\text{Collection Labor} = \text{Sampling Points} * \text{Collection Time} * \text{Monthly Frequency} * CF_{time} * \text{Labor Cost} \tag{9}$$

$$\text{Travel Labor} = \text{Monthly Frequency} * \text{Travel Time} * CF_{time} * \text{Labor Cost} \tag{10}$$

$$\text{Lab Cost} = \text{Sampling Points} * \text{Monthly Frequency} * CF_{time} * \text{Sample Cost} \tag{11}$$

$$\text{Annual Sampling Cost} = \text{Collection Labor} + \text{Travel Labor} + \text{Lab Cost} \tag{12}$$

Table 4-4 describes the variables in the sampling cost section of the caustic soda cost module shown in equations 9, 10, 11, and 12 and provides the values used in equations for both effluent scenarios.

Table 4-4. Sampling Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 12
CF_{time}	mo/yr	Conversion factor for converting months to years	12 mo/yr	Constant
Collection Labor	$/yr	Annual labor cost for worker to collect samples	NA	Calculated in Equation 9
Collection Time	hr	Average time expected for the worker to collect one sample	0.33 hr	*AMDTreat® v.4.1*
Lab Cost	$/yr	Annual cost for laboratory analysis	NA	Calculated in Equation 11
Labor Cost	$/hr	Hourly rate for worker	$ 35.00/hr	*AMDTreat® v.4.1*
Monthly Frequency	No./month	Number of samples collected per month	2/month	*AMDTreat® v.4.1*
Sample Cost	$/sample	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	*AMDTreat® v.4.1*

Table 4-4. Sampling Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Sampling Points	No.	Number of sampling points in treatment system	3	*AMDTreat® v.4.1* - Assumes sampling effluent and upstream and downstream of the discharge location
Travel Labor	$/yr	Annual labor cost for worker to travel to site	NA	Calculated in Equation 10
Travel Time	hr	Time expected for worker to travel from the office to the site	2 hr	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.4 Maintenance Cost

The maintenance costs include the cost of labor to maintain the system and the cost of replacing portions of the caustic soda storage system. The labor cost associated with maintaining the caustic soda chemical precipitation system is based on the weekly site visits required by the operator to ensure the system is operating correctly. Mr. Mark Tercek of PBS Coals, Inc. reported that active treatment systems, including chemical precipitation using caustic soda, require operators to check the site daily (Wolford, 2007c). The maintenance labor cost does not depend on effluent water characteristics but rather the type of treatment system; therefore, the maintenance labor cost is the same for both effluent scenarios. The replacement cost is based on the total capital cost of the caustic soda treatment system that is calculated in Section 4.2.2.

Equation 13 calculates maintenance cost, including the labor required to maintain the chemical precipitation system and the cost of replacing malfunctioning equipment.

Maintenance Cost = Visits per Week * {Labor Time + Travel Time} * Labor Cost * CF_{time} + Replacement Cost (13)

Equation 14 calculates the annual replacement cost of the caustic soda treatment system. This calculation assumes that the treatment system will be replaced periodically during the life of the system. The term "Rounddown{equation, 0} represents the number of times in the life of the system that the caustic soda storage system will need replaced. For example, if the caustic soda storage system life is 20 years and the system life is 75 years, the caustic soda storage system will need replaced three times in the 75 year treatment period.

Replacement Cost = $\frac{\text{Total Capital Cost}}{\text{System Life}}$ * Rounddown{ $\frac{\text{System Life}}{\text{Capital System Life}}$, 0} (14)

Table 4-5 describes the variables in the maintenance cost section of the caustic soda cost module shown in equations 13 and 14 and provides the values used in equations for both effluent scenarios.

Table 4-5. Maintenance Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Capital System Life	yr	Life span of the treatment system	20 yrs	EPA Assumption
CF_{time}	wk/yr	Conversion factor for converting weeks to years	52 wk/yr	Constant
Labor Cost	$/hr	Hourly rate for worker	$35/hr	*AMDTreat® v.4.1*
Labor Time	hr	Time expected for worker to inspect the treatment system and ensure its working correctly	2 hr	*AMDTreat® v.4.1*
Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 13
Replacement Cost	$/yr	Annual cost of replacing the treatment system	NA	Calculated in Equation 14
System Life	yr	Years the hydrated lime treatment system must treat the discharge	75 yrs	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)
Total Capital Cost	$	Total capital cost for hydrated lime system	NA	Calculated in Equation 18
Travel Time	hr	Time expected for worker to travel from the office to the site	2 hr	*AMDTreat® v.4.1*
Visits per Week	No./wk	Number of visits required to maintain the system per week	5/wk	Telecon with Mr. Tercek, PBS Coals (Tercek, 2007).

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.5 Total Annual Cost

Equation 14 can be used to calculate the total annual costs for the caustic soda chemical precipitation system.

Total Annual Cost = Annual Chemical Cost + Annual Sludge Cost + Annual Sampling Cost   (14)
    + Annual Maintenance Cost

Table 4-6 describes the variables in the total annual cost section of the caustic soda cost module shown in equation 14 and provides the values used in equations for both effluent scenarios. The total annual cost variables are the same for both effluent scenarios.

Table 4-6. Total Annual Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Chemical Cost	$/yr	Annual chemical cost	NA	Calculated in Equation 3
Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 13
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 12
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 8
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 14

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2 Capital Costs

The following sections describe the calculation of capital costs.

4.2.1 Caustic Soda Storage Tank Cost

EPA assumes that the caustic soda is purchased as a 99 percent solution and stored in storage tanks at the treatment system. The number of storage tanks required to store the annual caustic soda requirement depends on the storage tank size and chemical delivery frequency. The amount of caustic soda required is calculated in Section 4.1.1. EPA assumes that the caustic soda is delivered monthly and the storage tank is 2,500 gal.

Equation 15 can be used to calculate the number of storage tanks required to store the annual caustic soda. The term "Roundup{equation, 0}" represents the number of full tanks required to store all of the caustic soda because purchasing smaller tanks is not available. For example, if the system requires 4.2 storage tanks, the "Roundup" function changes the number to 5.

$$\text{Number of Tanks} = \text{Roundup}\left\{\frac{NaOH_{req}}{\text{Tank Volume * Delivery Frequency}}, 0\right\} \tag{15}$$

Equation 16 can be used to calculate the cost of the storage tanks.

$$\text{Storage Tank Cost} = \text{Number of Tanks * Tank Cost} \tag{16}$$

Table 4-7 describes the variables in the caustic soda storage tank cost section of the caustic soda cost module shown in equations 15 and 16 and provides the values used in the equations for each effluent scenario.

Table 4-7. Caustic Soda Storage Tank Cost Variable Descriptions

| Variable | Units | Variable Description | Effluent Scenario 1[a] and 2[b] | |
			Value	Value Source
Delivery Frequency	No./yr	Annual delivery frequency of caustic soda	12/yr	*AMDTreat® v.4.1*
NaOH$_{req}$	gal/yr	Amount of caustic soda required to neutralize the net acidity	NA	Calculated in Equation 2
Number of Tanks	No.	Number of tanks required	NA	Calculated in Equation 15
Storage Tank Cost	$	Total cost of storage tanks required	NA	Calculated in Equation 16
Tank Cost	$	Cost of storage tank	$ 2,000	*AMDTreat® v.4.1*
Tank Volume	gal	Size of caustic soda storage tank	2,500 gal	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2.2   Total Capital Costs

The total capital cost includes the cost of the caustic soda storage tank(s), valves and piping, installation labor, chemical metering pump, and pH monitoring to ensure the correct amount of caustic soda is added. This cost module assumes that the number of valves, feeder line length, and installation system cost are independent of the number of caustic soda storage tanks and therefore are the same for both effluent scenarios. However, these costs are included for comparison to other cost modules for EPA's Detailed Study of the Coal Mining Industry.

Equation 17 can be used to calculate the piping costs for the caustic soda chemical precipitation system.

Total Piping Cost = Valve Cost * Valves + Pipe Length * Pipe Cost + Pump Cost + pH Controller + pH Probe   (17)

Equation 18 can be used to calculate the total capital costs for the caustic soda chemical precipitation system.

Total Capital Cost = Storage Tank Cost + Installation Cost * Installation Hours + Total Piping Cost   (18)

Table 4-8 describes the variables in the total capital cost section of the caustic soda cost module shown in equations 17 and 18 and provides the values used in the equations for each effluent scenario.

Table 4-8. Total Capital Cost Variable Descriptions

| Variable | Units | Variable Description | Effluent Scenario 1[a] and 2[b] | |
			Value	Value Source
Installation Cost	$/hr	Hourly cost for installation of caustic soda system	$ 35/hr	*AMDTreat® v.4.1*
Installation Hours	hr	Hours to install the caustic soda system	8 hr	*AMDTreat® v.4.1*

Table 4-8. Total Capital Cost Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
pH Controller	$	Cost of PID pH proportional controller	$ 1,875	*AMDTreat® v.4.1*
pH Probe	$	Cost of pH probe	$ 550	*AMDTreat® v.4.1*
Pipe Cost	$/ft	Pipe cost	$ 0.35/ft	*AMDTreat® v.4.1*
Pipe Length	ft	Piping length	20 ft	*AMDTreat® v.4.1*
Pump Cost	$	Cost of chemical metering pump	$ 3,000	*AMDTreat® v.4.1*
Storage Tank Cost	$	Total cost of storage tanks required	NA	Calculated in Equation 16
Total Capital Cost	$	Total capital cost for caustic soda system	NA	Calculated in Equation 18
Total Piping Cost	$	Total cost of piping, valves, and pump and valves for caustic soda system	NA	Calculated in Equation 17
Valve Cost	$/valve	Cost of valves for caustic soda system	$ 50/valve	*AMDTreat® v.4.1*
Valves	No.	Number of valves in caustic soda system	2	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.3   **Effluent Scenario Cost Comparison**

EPA is estimating the cost difference between using chemical precipitation and other treatment technologies to achieve two different effluent scenarios:

1.   To meet all of the 40 CFR Part 434 limits (TSS, pH, iron, and manganese); and
2.   To meet only the TSS, pH, and iron limits in 40 CFR Part 434.

Prior to calculating the cost difference, the capital costs must be annualized for each effluent scenario. Equations 19 and 20 calculate the total annualized costs for the caustic soda chemical precipitation system.

$$\text{Annualized Capital Cost} = \text{Total Capital Cost} * \frac{\{\text{Interest} * (1 + \text{Interest})^{\text{years}}\}}{(1 + \text{Interest})^{\text{years}} - 1} \tag{19}$$

$$\text{Total Annualized Cost} = \text{Annualized Capital Cost} + \text{Total Annual Cost} \tag{20}$$

Equation 21 compares the total annualized cost for effluent scenario 1 with the total annualized cost for effluent scenario 2.

$$\text{Net Annual Cost} = \text{Total Annualized Cost}_{\text{Effluent Scenario 1}} - \text{Total Annualized Cost}_{\text{Effluent Scenario 2}} \tag{21}$$

Table 4-9 describes the variables in the effluent scenario cost comparison section of the caustic soda cost module shown in equations 19, 20, and 21 and provides the values used in the equations for each effluent scenario.

Table 4-9. Effluent Scenario Cost Comparison Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annualized Capital Cost	$/yr	Annualized capital cost for caustic soda treatment system	NA	Calculated in Equation 19
Interest	%	Interest rate for annualization	10 %	EPA
Net Annual Cost	$/yr	Net annual cost to increase from pH 8.3 to pH 10 using caustic soda treatment system	NA	Calculated in Equation 21
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 14
Total Annualized Cost	$/yr	Total annualized cost (capital and annual) for caustic treatment system	NA	Calculated in Equation 20
Total Capital Cost	$	Total capital cost for caustic soda system	NA	Calculated in Equation 18
Years	yr	Years for annualization calculation	75 yr	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

5.0 REFERENCES

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Attachment A – *AMDTreat*[®] *v.4.1* **Default Values for Caustic Soda Chemical Precipitation Cost Module**

Table A-1. *AMDTreat*® *v.4.1* **Default Values for the Caustic Soda Chemical Precipitation Cost Module**

Variable	Variable Description	*AMDTreat*® *v.4.1* Default Value	Equation Reference
% Solids	Ratio of the weight of solids to the weight of water	5 %	4, 5, 6, 7
Caustic Soda Cost	Cost of caustic soda	$ 0.70/gal	3
Collection Time	Average time expected for the worker to collect one sample	0.33 hr	9
Delivery Frequency	Annual delivery frequency of caustic soda	12/yr	15
Density$_{NaOH}$	Density of 99 % purity sodium hydroxide solution	0.49 lb/gal	2
Density$_{Sludge}$	Density of solids and water in sludge	8.33 lb/gal	4, 5, 6, 7
Efficiency	Mixing efficiency of caustic soda with discharge	100 %	2
Installation Cost	Hourly cost for installation of caustic soda system	$ 35/hr	18
Installation Hours	Hours to install the caustic soda system	8 hr	18
Labor Cost	Hourly rate for worker	$ 35.00/hr	9, 10, 13
Labor Time	Time expected for worker to inspect the treatment system and ensure its working correctly	2 hr	13
Monthly Frequency	Number of samples collected per month	2/month	9, 10, 11
pH Controller	Cost of PID pH proportional controller	$ 1,875	17
pH Probe	Cost of pH probe	$ 550	17
Pipe Cost	Pipe cost	$ 0.35/ft	17
Pipe Length	Piping length	20 ft	17
Pump Cost	Cost of chemical metering pump	$ 3,000	17
Purity	Purity of caustic soda	99 %	2
Removal Cost	Cost of removing sludge	$ 0.06/gal	8
Sample Cost	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	11
Sampling Points	Number of sampling points in treatment system	3	9, 11
Tank Cost	Cost of storage tank	$ 2,000	16
Tank Volume	Size of caustic soda storage tank	2,500 gal	15
Travel Time	Time expected for worker to travel from the office to the site	2 hr	10, 13
Valve Cost	Cost of valves for caustic soda system	$ 50/valve	17
Valves	Number of valves in caustic soda system	2	17

Appendix C

DRAFT ACID MINE DRAINAGE TREATMENT COST MODULE: CHEMICAL PRECIPITATION USING CAUSTIC SODA

Draft Acid Mine Drainage Treatment Cost Module:
Chemical Precipitation Using Hydrated Lime
August 16, 2007

Disclaimer: This is a <u>draft</u> module for a cost estimation tool. EPA developed this module for the Detailed Study of the Coal Mining Point Source Category (40 CFR Part 434) to estimate the cost difference between treating acid mine drainage (AMD) using hydrated lime chemical precipitation over a range of flows:

- To meet all of the 40 CFR Part 434 limits (TSS, pH, iron, and manganese); and
- To meet only the TSS, pH, and iron limits in 40 CFR Part 434.

The costs are based on calculations and default values provided in the *AMDTreat*® software that was developed cooperatively by the Pennsylvania Department of Environmental Protection (PA DEP), West Virginia Department of Environmental Protection (WV DEP), and the U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE). The default values from *AMDTreat*® that are used in the lime chemical precipitation module are presented in Attachment A.

OSMRE verifies treatment costs roughly annually, and the most recent version of *AMDTreat*®, version 4.1, expresses costs in 2006 dollars. *AMDTreat*® *v.4.1* has not been peer reviewed (Wolford, 2007a).

1.0   MODULE METHODOLOGY

This module estimates the costs associated with installing and operating a hydrated lime $(Ca(OH)_2)$ chemical precipitation system for treating AMD. Chemical precipitation using hydrated lime has been used widely to neutralize acidity and precipitate metal ions in AMD since the passage of the Surface Mining, Control, and Reclamation Act of 1977 (SMCRA) and the Coal Mining Effluent Guidelines and Standards (40 CFR Part 434). EPA is estimating the cost difference between using chemical precipitation to achieve two different effluent scenarios:

- To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
- To meet only the TSS, pH, and iron limitations of 40 CFR Part 434.

40 CFR Part 434 defines AMD as mine drainage that, before treatment, either has a pH of less than 6.0 or a total iron concentration equal to or greater than 10 mg/L. The limitations for AMD are in 40 CFR Part 434 Subpart C, shown in Table 1-1 (BAT) and Table 1-2 (NSPS). The best available control technology (BAT) limitations apply to coal mines that were constructed prior to May 4, 1984. The new source performance standards (NSPS) limitations apply to coal mines that were constructed after May 4, 1984. EPA assumes that the majority of the coal mines are required to meet the NSPS limitations and will use the limitations presented in Table 1-2 for the effluent scenarios.

Table 1-1. BAT Effluent Guidelines for Coal Mining Part 434, Subpart C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.5	7.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.
[a]Subpart C – Acid of Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Industry.

Table 1-2. NSPS Effluent Guidelines for Coal Mining Part 434, Subpart C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.
[a]Subpart C – Acid of Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Industry.

Under the first effluent scenario, EPA estimates the cost to remove pollutants to meet all the NSPS limitations in Table 1-2. Under the second effluent scenario, EPA estimates the costs to remove all pollutants except manganese to the NSPS limitations level required by 40 CFR Part 434 presented in Table 1-2.

1.1 Process Description

Chemical precipitation is widely used in the coal mining industry to meet NPDES permit limitations. This section describes chemical precipitation in general (Section 2.1) and how it specifically applies to AMD (Section 2.2).

1.2 Chemical Precipitation

Chemical precipitation involves removing metallic contaminants from aqueous solutions by converting soluble, heavy metals to insoluble salts. The precipitated solids are then removed from solution by flocculation followed by sedimentation and/or filtration. Precipitation is caused by the addition of chemical reagents that adjust the pH of the water to the minimum solubility of the metal. The standard reagents include the following (U.S. EPA, 2000):

- Lime (calcium hydroxide);
- Caustic (sodium hydroxide);
- Magnesium hydroxide;
- Soda ash (sodium carbonate);

- Trisodium phosphate;
- Sodium sulfide; and
- Ferrous sulfide.

These reagents precipitate metals as hydroxides, carbonates, phosphates, and sulfates. The precipitated metals form sludge. Over time, the accumulated sludge must be removed from the treatment system.
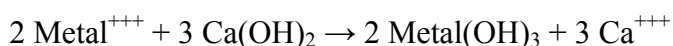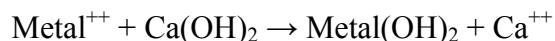
1.3   Chemical Precipitation of AMD

The majority of coal mines treating AMD use lime or caustic for precipitation. Metals commonly targeted for removal from solution by precipitation include iron, manganese, and aluminum.

Figure 2-1 shows an example hydrated lime chemical precipitation process:

- The AMD is aerated, often by gravity flow and sprays, to increase the dissolved oxygen in the discharge. The increased dissolved oxygen allows some metals to oxidize and form metal hydroxides, such as ferric hydroxide (Fe(OH)3).
- The first settling pond removes the majority of the metal hydroxides that formed due to aeration.
- The hydrated lime chemical precipitant is added to the discharge in a mixing tank to create a slurry solution of hydrated lime and untreated AMD. The remaining dissolved metals, such as manganese and magnesium, are oxidized to an insoluble form in the mixing tank.
- The remaining settling ponds remove the suspended insoluble metal hydroxides.

Hydroxide precipitation normally involves using lime ($Ca(OH)_2$) or caustic soda (NaOH) as a precipitant to remove metals as insoluble metal hydroxides. The reaction is illustrated by the following equations for precipitation of divalent and trivalent metals using lime:

$$Metal^{++} + Ca(OH)_2 \rightarrow Metal(OH)_2 + Ca^{++}$$

$$2\ Metal^{+++} + 3\ Ca(OH)_2 \rightarrow 2\ Metal(OH)_3 + 3\ Ca^{+++}$$

The effluent metals concentration attained by hydroxide precipitation depends on the metals present and reaction conditions. Many scientists have studied metals removal from AMD, particularly the difficulty of removing manganese. Two studies in particular address EPA's question of the incremental cost to remove manganese:

- Kirby and Cravotta: Net Alkalinity and Net Acidity 1: Theoretical Considerations (Kirby, 2005a) and Net Alkalinity and Net Acidity 2: Practical Considerations (Kirby, 2005b). Attachment B contains these articles.
- Means and Hilton: Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage (Means, 2004). Attachment C contains this article.

While scientists have found that iron will precipitate quickly at a pH near 7, manganese precipitates quickly only when the pH is raised to 9 or 10 (Means, 2004). Figure 2-2 illustrates the solubility curves from research performed by Dr. Chuck Cravotta, U.S.G.S., for metals commonly in AMD, showing solubilities relative to pH.
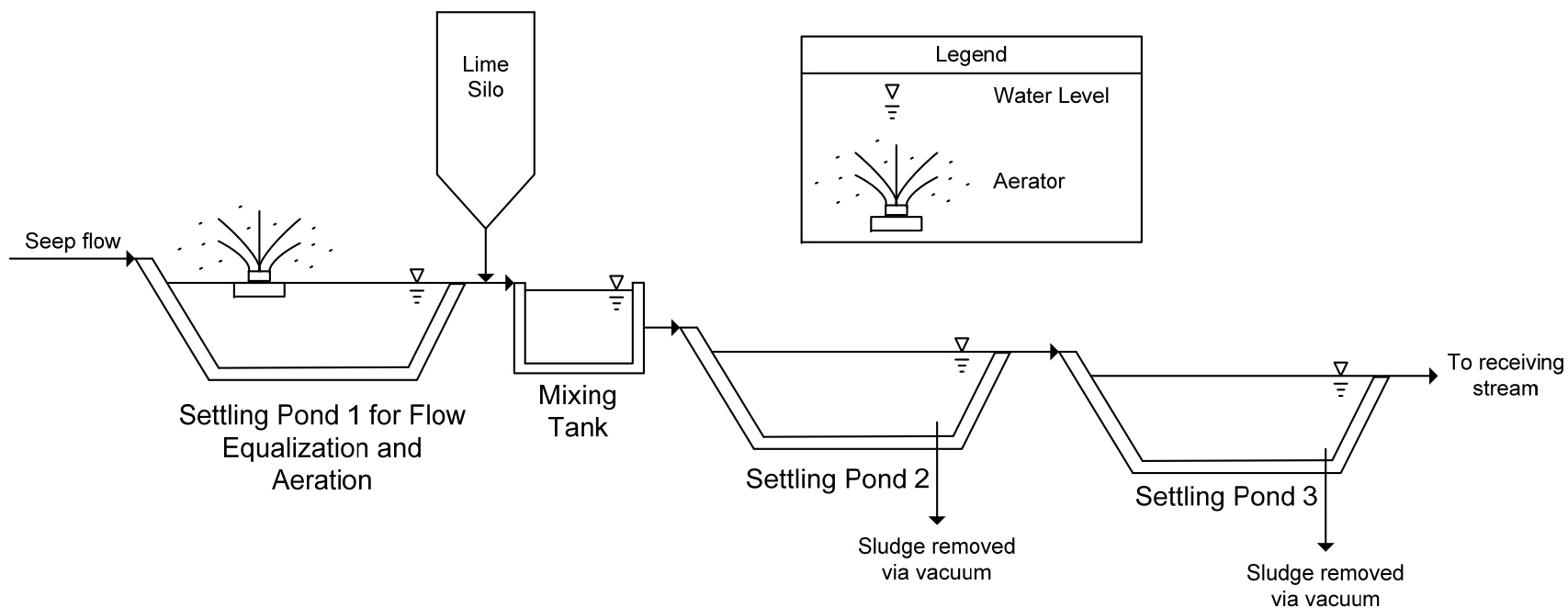
Lime
Silo

Legend

Water Level

Aerator

Seep flow

Settling Pond 1 for Flow
Equalization and
Aeration

Mixing
Tank

Settling Pond 2

Settling Pond 3

Sludge removed
via vacuum

Sludge removed
via vacuum

To receiving
stream

Figure 2-1. Example AMD Chemical Precipitation Treatment System using Hydrated Lime

Figure 2-2. Comparison of Metal Hydroxide Solubilities for Constituents Commonly Found in Acidic Mine Drainage (Means, 2004)

2.0   DESIGN CONSIDERATIONS

This cost module considers the costs required for chemical precipitation using hydrated lime ($Ca(OH)_2$). EPA is estimating the cost of treating AMD with chemical precipitation using caustic (NaOH) and with a limestone bed in separate cost modules (see "Draft Acid Mine Drainage Treatment Cost Module: Chemical Precipitation Using Caustic Soda" and "Draft Acid Mine Drainage Treatment Cost Module: Limestone Bed," both dated August 2007 (see Appendix C and E of the Coal Mining Detailed Study Report)). EPA considered the amount of hydrated lime required to adjust the pH to a given level, the amount of sludge generated and the cost of its removal, and the required operating labor.

EPA assumes that the annual costs for electricity and land requirements are approximately equal under both effluent scenarios. For this reason, EPA did not consider the cost of obtaining or leasing the land for the treatment system or other capital equipment costs or electricity needs in its estimate of annual costs.

3.0   COST MODULE CALCULATIONS

EPA is estimating costs to treat AMD with chemical precipitation using hydrated lime to achieve two different effluent scenarios:

- To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
- To meet only the TSS, pH, and iron limitations of 40 CFR Part 434.

Table 4-1 presents the limits for each of the effluent scenarios. The difference between the effluent scenarios is that effluent scenario 1 meets the current manganese limits while effluent scenario 2 does not incorporate any change in manganese concentration. For calculation purposes, only the 30-day limit is considered, because it is lower than the daily maximum limit.

Table 4-1. Effluent Discharge Limitations for Effluent Scenarios

Parameter	Effluent Scenario 1		Effluent Scenario 2	
	NSPS 30-Day Average (mg/L)	NSPS Daily Maximum (mg/L)	NSPS 30-day Average (mg/L)	NSPS Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70	35	70
pH	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0	3.0	6.0
Manganese, Total	2.0	4.0	NA	NA

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.

The first effluent scenario will be achieved by treating the AMD to pH 10 using hydrated lime, based on the solubility of the metals. EPA assumes that at pH 10 the effluent will result in the following characteristics based on the metals solubilities from Figure 2-2 (Means, 2004):[1]

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

Although the hydrated lime addition results in pH 10 for effluent scenario 1, after the settling ponds where the metal hydroxides are removed the pH will decrease and meet the limitation in Table 4-1 prior to discharge.

The second effluent scenario will be achieved by treating the AMD to pH 8.3 using hydrated lime. EPA assumes that at pH 8.3 the effluent will result in the following characteristics based on the metals solubilities from Figure 2-2 (Means, 2004):[2]

- Iron at 3.0 mg/L;
- A 10 percent reduction in magnesium from untreated;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

Additionally, the final pH will remain in the range of 6 to 9 to meet the limitation.

For both effluent scenarios the cost module includes the following items:

- Annual Costs (Section 4.1) including;
  — Chemicals cost (Section 4.1.1);
  — Sludge removal cost (Section 4.1.2);
  — Sampling cost (Section 4.1.3); and
  — Maintenance cost (Section 4.1.4) that includes maintenance labor and the annual cost for replacement of chemical storage system every 20 years.
- Capital Costs (Section 4.2) including:
  — Chemicals storage cost (Section 4.2.1); and
  — Mixing tank cost (Section 4.2.2).

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[1] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.
[2] Ibid.

The sampling cost and maintenance cost will be the same for each effluent scenario because these portions of the cost module do not depend on effluent water characteristics. Therefore, the sampling cost and maintenance cost for each effluent scenario will off-set when the total costs are compared. However, these costs are included for comparison to other costing modules in EPA's Detailed Study of the Coal Mining Industry.

3.1 Annual Costs

The following sections describe the calculations of annual costs.

3.1.1 Chemical Cost

Under the first effluent scenario, EPA is estimating the cost of hydrated lime to reach approximately pH 10. EPA assumes that at pH 10 the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) and manganese (2 mg/L 30-day average) limitations based on the solubility of these metals, presented in Figure 2-2 (Means, 2004). Under the second effluent scenario, EPA is estimating the cost of hydrated lime to reach approximately pH 8.3. EPA assumes that at pH 8.3 the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) limitation but will not meet the manganese (2 mg/L 30-day average) limitation (Means, 2004).[3]

The amount of hydrated lime required annually depends on three things:

1. Net acidity;
2. Discharge flow rate; and
3. The additional acidity required to increase the pH to the desired level.

The net acidity is estimated based on pH, metals concentrations (specifically ferrous and ferric iron, manganese, and aluminum), additional acidity liberated to achieve pH 10, and alkalinity. Equation 1 calculates the net acidity.

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[3] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumptions that 1) a multiplier of 4 accounts for the additional acidity liberated when raising pH to 10 to settle manganese and 2) that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. 1) Mine drainage chemistry is complex and variable. In some AMD, as demonstrated in *Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004), there may be little additional acidity liberated when titrating pH to 10. For AMD with these characteristics, the multiplier of 4 overestimates the amount of treatment chemical required to adjust pH for manganese treatment. 2) Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.

Net Acidity = 50*{(1000*10^{-pH}) + $\dfrac{2*Fe^{2+}+3*Fe^{3+}}{55.842}$ + $\dfrac{2*Mn}{54.93807}$ $\dfrac{3*Al}{26.9815386}$ } * Acidity Multiplier – Alkalinity   (1)

where:
- Acidity Multiplier. A factor accounting for additional acidity liberated to achieve pH 10;
- Net acidity. Laboratory-measured acidity; and
- Alkalinity. Laboratory-measured alkalinity.

The acidity multiplier is derived from the Means and Hilton article entitled *Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage*, in Attachment C. The scientists found that the Standard Method (SM) 2310 for hot acidity is often not a valid expression of acidity for waters with pH's greater than 8.2. The article concludes that when adding caustic to adjust pH for manganese precipitation (i.e., to increase the pH to 10), plant operators must consider the amount of caustic consumed by magnesium and other ions. The amount of caustic consumed by magnesium and other ions at pH's above 10 is not accounted for by SM 2310. (Means, 2004)

As a result, EPA used data from the Means and Hilton article to estimate the additional caustic needed when adjusting pH above 8.3. Means and Hilton provide data for four different discharges of AMD (Means, 2004). EPA selected the "worst case scenario," or the data for the AMD requiring the greatest additional caustic to increase the pH to 10, for manganese removal. The data demonstrate that to adjust pH from 8.3 to 10, roughly three times the amount of caustic is necessary, and the acidity multiplier is 4.

The amount of hydrated lime required to achieve a specific pH is based on the net acidity is based on the discharge flow rate, mixing efficiency, and caustic soda purity. Equation 2 calculates the amount of hydrated lime required to achieve a specific pH (pH 10 for effluent scenario 1 and pH 8.3 for effluent scenario 2).

$Ca(OH)_{2,req}$ = Net Acidity * Flow * $\dfrac{MW_{Ca(OH)2}}{MW_{CaCO3}}$ * $\dfrac{100}{Purity}$ * $\dfrac{100}{Efficiency}$ * CF_{weight} * CF_{time} * CF_{volume} (2)

Equation 3 calculates the annual cost of hydrated lime required to neutralize the net acidity.

Annual Chemical Cost = $Ca(OH)_{2,req}$ * Hydrated Lime Cost   (3)

Table 4-2 describes the variables in the chemical cost section of the hydrated lime cost module shown in equations 1, 2, and 3 and provides the values used in the equations for each effluent scenario.

Table 4-2. Chemical Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] Value	Effluent Scenario 1[a] Value Source	Effluent Scenario 2[b] Value	Effluent Scenario 2[b] Value Source
Acidity Multiplier	None	Multiplier of additional acidity liberated when increasing the pH from 8.3 to 10	4	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	0	*Net Alkalinity and Net Acidity 2: Practical Considerations* (Kirby, 2005b)
Alkalinity	mg $CaCO_3$/L	Alkalinity in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Annual Chemical Cost	$/yr	Annual cost of hydrated lime	NA	Calculated in Equation 3	NA	Calculated in Equation 3
$Ca(OH)_{2,req}$	lb/yr	Amount of 96 % purity hydrated lime required to neutralize net acidity	NA	Calculated in Equation 2	NA	Calculated in Equation 2
CF_{time}	min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
CF_{volume}	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
CF_{weight}	lb/mg	Conversion factor for converting pounds to milligrams	2.205×10^{-6} lb/mg	Constant	2.205×10^{-6} lb/mg	Constant
Efficiency	%	Mixing efficiency of hydrated lime with discharge	80 %	*AMDTreat® v.4.1*	80 %	*AMDTreat® v.4.1*
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Flow	gal/min	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Hydrated Lime Cost	$/lb	Cost of hydrated lime	$ 0.10/lb	*AMDTreat® v.4.1*	$ 0.10/lb	*AMDTreat® v.4.1*
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$MW_{Ca(OH)2}$	g/mol	Molecular weight for hydrated lime	74.09268 g/mol	Constant	74.09268 g/mol	Constant
MW_{CaCO3}	g/mol	Molecular weight for hydrated lime	100.0869 g/mol	Constant	100.0869 g/mol	Constant

Table 4-2. Chemical Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Net Acidity	mg CaCO$_3$/L	Discharge net acidity	NA	Calculated in Equation 1	NA	Calculated in Equation 1
pH	Standard units	Untreated discharge pH	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Purity	%	Purity of hydrated lime	96 %	*AMDTreat® v.4.1*	96 %	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.1.2 Sludge Removal Cost

The sludge generated annually depends on the water chemistry, such as final pH and iron concentrations, and settling pond retention time. EPA assumes that when the discharge reaches pH 10 for effluent scenario 1, the following effluent quality will be achieved based on metal solubilities from Figure 2-2 (Means, 2004):[4]

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

EPA assumes that when the discharges reaches pH 8.3 for effluent scenario 2, the following effluent quality will be achieved based on metals solubilities from Figure 2-2 (Means, 2004):[5]

- Iron at 3.0 mg/L;
- A 10 percent reduction in magnesium from untreated;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

This cost module does not include the amount of sludge generated from other insoluble metal hydroxides; however, it overestimates sludge resulting from the iron, aluminum, manganese, and magnesium.

Equations 4, 5, 6, and 7 calculate the amount of sludge generated from aluminum, iron, manganese, and magnesium, respectively. Equation 8 calculates the annual sludge removal cost.

$$\text{Sludge}_{Al} = (Al * Al_{reduction}) * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \tag{4}$$

$$\text{Sludge}_{Fe} = \{(Fe^{3+} + Fe^{2+}) - Fe_{limit}\} * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \tag{5}$$

$$\text{Sludge}_{Mn} = (Mn - Mn_{limit}) * Mn_{reduction} * \text{Flow} * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{\text{Density}_{sludge}} * \frac{1}{\% \text{ Solids}} \tag{6}$$

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[4] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron. The costs estimated for sludge removal represent between 0.1 percent and 30 percent of the total annualized cost.

[5] Ibid.

$$\text{Sludge}_{Mg} = (Mg * Mg_{reduction}) * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \ Solids} \qquad (7)$$

$$\text{Annual Sludge Cost} = \{Sludge_{Al} + Sludge_{Fe} + Sludge_{Mn} + Sludge_{Mg}\} * \text{Removal Cost} \qquad (8)$$

Table 4-3 describes the variables in the sludge removal cost section of the hydrated lime cost module shown in equations 4, 5, 6, 7, and 8 and provides the values used in the equations for each effluent scenario.

Table 4-3. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
% Solids	%	Ratio of the weight of solids to the weight of water	5 %	*AMDTreat® v.4.1*	5 %	*AMDTreat® v.4.1*
Al	mg/L	Aluminum concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$Al_{reduction}$	%	Percent reduction of aluminum from untreated to final effluent	99 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	99 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 8	NA	Calculated in Equation 8
CF_{time}	min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
CF_{volume}	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
CF_{weight}	mg/lb	Conversion factor for converting milligrams to pounds	454,000 mg/lb	Constant	454,000 mg/lb	Constant
$Density_{sludge}$	lb/gal	Density of solids and water in sludge	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe_{limit}	mg/L	Effluent limit for iron	3.0 mg/L	40 CFR Part 434	3.0 mg/L	40 CFR Part 434
Flow	gpm	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mg	mg/L	Magnesium concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics

Table 4-3. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
$Mg_{reduction}$	mg/L	Percent reduction of magnesium from untreated to final effluent	10 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	0 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mn_{limit}	mg/L	Effluent limit for manganese	2.0 mg/L	40 CFR Part 434	0	Effluent value will be estimated based on performance data received from coal mines with chemical precipitation
Removal Cost	$/gal	Cost of removing sludge	$ 0.06/gal	*AMDTreat® v.4.1*	$ 0.06/gal	*AMDTreat® v.4.1*
$Sludge_{Al}$	gal/yr	Amount of sludge generated from the precipitation of aluminum	NA	Calculated in Equation 4	NA	Calculated in Equation 4
$Sludge_{Fe}$	gal/yr	Amount of sludge generated from the precipitation of iron	NA	Calculated in Equation 5	NA	Calculated in Equation 5
$Sludge_{Mg}$	gal/yr	Amount of sludge generated from the precipitation of magnesium	NA	Calculated in Equation 7	NA	Calculated in Equation 7
$Sludge_{Mn}$	gal/yr	Amount of sludge generated from the precipitation of manganese	NA	Calculated in Equation 6	NA	Calculated in Equation 6

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.1.3 Sampling Cost

The annual sampling cost includes the labor for collecting the samples and the sampling lab analysis costs. This cost module assumes that the number of samples required yearly is independent of the flow, net acidity, raw AMD metals concentrations, or treatment technology. Based on conversations with coal mine wastewater treatment operators, sampling is only conducted to meet the NPDES permit requirements (Wolford, 2007b; Wolford, 2007c). The sampling costs for both effluent scenarios are the same because sampling requirements are independent of effluent quality. EPA included the sampling cost anyway.

Equations 9, 10, 11, and 12 calculate the annual sampling cost assuming the NPDES permits require bi-monthly sampling.

Collection Labor = Sampling Points * Collection Time * Monthly Frequency * CF_{time} * Labor Cost   (9)

Travel Labor = Monthly Frequency * Travel Time * CF_{time} * Labor Cost   (10)

Lab Cost = Sampling Points * Monthly Frequency * CF_{time} * Sample Cost   (11)

Annual Sampling Cost = Collection Labor + Travel Labor + Lab Cost   (12)

Table 4-4 describes the variables in the sampling cost section of the hydrated lime cost module shown in equations 9, 10, 11, and 12 and provides the values used in equations for both effluent scenarios.

Table 4-4. Sampling Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 11
CF_{time}	mo/yr	Conversion factor for converting months to years	12 mo/yr	Constant
Collection Labor	$/yr	Annual labor cost for worker to collect samples	NA	Calculated in Equation 8
Collection Time	hr	Average time expected for the worker to collect one sample	0.33 hr	AMDTreat® v.4.1
Lab Cost	$/yr	Annual cost for laboratory analysis	NA	Calculated in Equation 10
Labor Cost	$/hr	Hourly rate for worker	$ 35.00/hr	AMDTreat® v.4.1
Monthly Frequency	No./month	Number of samples collected per month	2/month	AMDTreat® v.4.1
Sample Cost	$/sample	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	AMDTreat® v.4.1
Sampling Points	No.	Number of sampling points in treatment system	3	AMDTreat® v.4.1-Assumes sampling effluent and upstream and downstream of the discharge location

Table 4-4. Sampling Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Travel Labor	$/yr	Annual labor cost for worker to travel to site	NA	Calculated in Equation 9
Travel Time	hr	Time expected for worker to travel from the office to the site	2 hr	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.1.4 Maintenance Cost

The maintenance costs include the cost of labor to maintain the system and the cost of replacing portions of the hydrated lime storage system. The labor cost associated with maintaining the hydrated lime chemical precipitation system is based on the weekly site visits required by the operator to make sure the system is operating correctly. Mr. Mark Tercek of PBS Coals, Inc. reported that active treatment systems, including chemical precipitation using hydrated lime, require operators to check the site daily (Wolford, 2007c). The maintenance labor cost does not depend on effluent water characteristics but rather the type of treatment system; therefore, the maintenance labor cost is the same for both effluent scenarios. The replacement cost is based on the total capital cost of the hydrated lime treatment system that is calculated in Section 4.2.3.

Equation 13 calculates the maintenance cost, including the labor required to maintain the chemical precipitation system and cost of replacing malfunctioning equipment.

$$\text{Maintenance Cost} = \text{Visits per Week} * \{\text{Labor Time} + \text{Travel Time}\} * \text{Labor Cost} * CF_{time} + \text{Replacement Cost} \quad (13)$$

Equation 14 calculates the annual replacement cost of the hydrated lime treatment system. This calculation assumes that the treatment system will be replaced periodically to allow treatment to continue for the life of the system. The term "Rounddown{equation, 0}" represents the number of times in the life of the system that the hydrated lime storage system will need replaced. For example, if the hydrated lime storage system life is 20 years and the system life is 75 years, the hydrated lime storage system will need replaced three times in the 75 year treatment period.

$$\text{Replacement Cost} = \frac{\text{Total Capital Cost}}{\text{System Life}} * \text{Rounddown}\left\{\frac{\text{System Life}}{\text{Capital System Life}}, \; 0\right\} \quad (14)$$

Table 4-5 describes the variables in the maintenance labor cost section of the hydrated lime cost module shown in equations 13 and 14 and provides the values used in equations for both effluent scenarios.

Table 4-5. Maintenance Labor Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Capital System Life	yr	Life span of the treatment system	20 yrs	EPA Assumption
CF_{time}	wk/yr	Conversion factor for converting weeks to years	52 wk/yr	Constant
Labor Cost	$/hr	Hourly rate for worker	$ 35.00/hr	*AMDTreat® v.4.1*
Labor Time	hr	Time expected for worker to inspect the treatment system and ensure it's working correctly	2 hr	*AMDTreat® v.4.1*
Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 13
Replacement Cost	$/yr	Annual cost of replacing the treatment system	NA	Calculated in Equation 14
System Life	yr	Years the hydrated lime treatment system must treat the discharge	75 yrs	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)
Total Capital Cost	$	Total capital cost for hydrated lime system	NA	Calculated in Equation 35
Travel Time	hr	Time expected for worker to travel from the office to the site	2 hr	*AMDTreat® v.4.1*
Visits per Week	No./wk	Number of visits required to maintain the system per week	5/wk	Personal communication with Mr. Mark Tercek, PBS Coals, Inc. (Wolford, 2007c)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.1.5 Total Annual Costs

Equation 15 calculates the total annual costs for the hydrated lime chemical precipitation system.

Total Annual Cost = Annual Chemical Cost + Annual Sludge Cost + Annual Sampling Cost   (15)
       + $Annual Maintenance

Table 4-6 describes the variables in the total annual cost section of the hydrated lime cost module shown in equation 15 and provides the values used in the equations for both effluent scenarios. The total annual cost variables are the same for both effluent scenarios.

Table 4-6. Total Annual Cost Variable Descriptions

| Variable | Variable Units | Variable Description | Effluent Scenario 1[a] and 2[b] | |
			Value	Value Source
Annual Chemical Cost	$/yr	Annual chemical cost	NA	Calculated in Equation 3
Annual Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 13
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 12
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 8
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 15

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.2   Capital Costs

The capital costs for a hydrated lime chemical precipitation system include the following items:

- Hydrated lime storage silos;
- Mixing tank; and
- Valves and piping.

The following sections describe how each of these costs is calculated in the hydrated lime chemical precipitation module.

3.2.1   Hydrated Lime Storage Silo Cost

EPA assumes that the hydrated lime is purchased as fine powder containing 96 percent calcium hydroxide that is stored in storage silos. The number of storage silos required to store the hydrated lime depends on the storage silo size and hydrated lime delivery frequency.   EPA assumes that the hydrated lime is delivered monthly and the storage silo sizes are 2,000 tons, 3,500 tons, 5,000 tons, and 6,000 tons.

Equation 16 calculates the monthly hydrated lime from the annual hydrated lime calculated in Section 4.1.1.

$$\text{Monthly Hydrated Lime} = \frac{Ca(OH)_{2,req}}{CF_{time} * CF_{weight}} \tag{16}$$

Equations 17, 18, 19, 20, and 21 calculate the size of the storage silos in the hydrated lime chemical precipitation treatment system.

Silo 1 = if{Monthly Hydrated Lime < 20, 20, if{Monthly Hydrated Lime <35, 35,   (17)
        if{Monthly Hydrated Lime < 50, 50, 60}}}

Silo 2 = if{(Monthly Hydrated Lime – 60) < 0, 0, if{(Monthly Hydrated Lime – 60) < 20, 20,   (18)
    if{(Monthly Hydrated Lime – 60) < 35, 35, if{(Monthly Hydrated Lime – 60) < 50, 50, 60}}}}

Silo 3 = if{(Monthly Hydrated Lime – 120) < 0, 0, if{(Monthly Hydrated Lime – 120) < 20, 20,   (19)
    if{(Monthly Hydrated Lime – 120) < 35, 35, if{(Monthly Hydrated Lime – 120) < 50, 50, 60}}}}

Silo 4 = if{(Monthly Hydrated Lime – 180) < 0, 0, if{(Monthly Hydrated Lime – 180) < 20, 20,   (20)
    if{(Monthly Hydrated Lime – 180) < 35, 35, if{(Monthly Hydrated Lime – 180) < 50, 50, 60}}}}

Silo 5 = if{(Monthly Hydrated Lime – 240) < 0, 0, if{(Monthly Hydrated Lime – 240) < 20, 20,   (21)
    if{(Monthly Hydrated Lime – 240) < 35, 35, if{(Monthly Hydrated Lime – 240) < 50, 50, 60}}}}

Equations 22, 23, 24, 25, 26, and 27 calculate the cost of each storage silo and the total silo cost for the hydrated lime storage system.

Silo 1 Cost = if{Silo 1 = 20, $Cost_{20}$, if{Silo 1 = 35, $Cost_{35}$, if{Silo 1 = 50, $Cost_{50}$, $Cost_{60}$}}}   (22)

Silo 2 Cost = if{Silo 2 = 0, 0, if{Silo 2 = 20, $Cost_{20}$, if{Silo 2 = 35, $Cost_{35}$, if{Silo 2 = 50, $Cost_{50}$, $Cost_{60}$}}}}   (23)

Silo 3 Cost = if{Silo 3 = 0, 0, if{Silo 3 = 20, $Cost_{20}$, if{Silo 3 = 35, $Cost_{35}$, if{Silo 3 = 50, $Cost_{50}$, $Cost_{60}$}}}}   (24)

Silo 4 Cost = if{Silo 4 = 0, 0, if{Silo 4 = 20, $Cost_{20}$, if{Silo 4 = 35, $Cost_{35}$, if{Silo 4 = 50, $Cost_{50}$, $Cost_{60}$}}}}   (25)

Silo 5 Cost = if{Silo 5 = 0, 0, if{Silo 5 = 20, $Cost_{20}$, if{Silo 5 = 35, $Cost_{35}$, if{Silo 5 = 50, $Cost_{50}$, $Cost_{60}$}}}}   (26)

Total Silo Cost = Silo 1 Cost + Silo 2 Cost + Silo 3 Cost + Silo 4 Cost + Silo 5 Cost   (27)

Table 4-7 describes all the variables in the hydrated lime storage silo cost section of the hydrated lime cost module shown in equations 16 through 27 and provides the values used in the equations for each effluent scenario.

Table 4-7. Total Annual Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
CF_{time}	mo/year	Conversion factor for converting months to years	12 mo/yr	Constant
CF_{weight}	lb/ton	Conversion factor for converting pounds to tons	2,000 lb/ton	Constant
$Ca(OH)_{2,req}$	lb/yr	Amount of hydrated lime required to achieve pH 10	NA	Calculated in Equation 2
Monthly Hydrated Lime	ton/month	Amount of hydrated lime required to achieve pH 10	NA	Calculated in Equation 16
Silo 1	ton	Silo size for first silo in treatment system	NA	Calculated in Equation 17
Silo 2	ton	Silo size for second silo in treatment system	NA	Calculated in Equation 18
Silo 3	ton	Silo size for third silo in treatment system	NA	Calculated in Equation 19
Silo 4	ton	Silo size for fourth silo in treatment system	NA	Calculated in Equation 20

Table 4-7. Total Annual Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Silo 5	ton	Silo size for fifth silo in treatment system	NA	Calculated in Equation 21
$Cost_{20}$	$	Cost of 20 ton silo	$ 25,000	*AMDTreat*® *v.4.1*
$Cost_{35}$	$	Cost of 35 ton silo	$ 27,000	*AMDTreat*® *v.4.1*
$Cost_{50}$	$	Cost of 50 ton silo	$ 32,000	*AMDTreat*® *v.4.1*
$Cost_{60}$	$	Cost of 60 ton silo	$ 35,000	*AMDTreat*® *v.4.1*
Silo 1 Cost	$	Cost for first silo in treatment system	NA	Calculated in Equation 22
Silo 2 Cost	$	Cost for second silo in treatment system	NA	Calculated in Equation 23
Silo 3 Cost	$	Cost for third silo in treatment system	NA	Calculated in Equation 24
Silo 4 Cost	$	Cost for fourth silo in treatment system	NA	Calculated in Equation 25
Silo 5 Cost	$	Cost for fifth silo in treatment system	NA	Calculated in Equation 26
Total Silo Cost	$	Total cost for all silos in treatment system	NA	Calculated in Equation 27

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.2.2   Mixing Tank Cost

EPA assumes that the hydrated lime chemical precipitation system includes a mixing tank to add the powdered hydrated lime to the discharge. The mixing tank cost includes the excavation of soil for the below-grade mixing tank and the concrete required to form the tank. The size of the mixing tank is based on the discharge flow and retention time. EPA assumes that the mixing tank is square so the length and width are the same.

Equations 28, 29, and 30 calculate the mixing tank volume and dimensions.

$$\text{Tank Volume} = \text{Flow} * \text{Retention Time} \tag{28}$$

$$\text{Length} = \text{Width} = \frac{\{\text{Tank Volume}\}^{1/3}}{\{2 * CF_{volume,wet}\}^{1/3}} \tag{29}$$

$$\text{Depth} = 2 * \text{Length} \tag{30}$$

Equation 31 calculates the volume of soil that must be excavated for the mixing tank.

$$\text{Excavation Volume} = \{\text{Length} + \text{Wall}\} * \{\text{Width} + \text{Wall}\} * \{\text{Depth} + \text{Bottom} + \text{Freeboard}\} \tag{31}$$

Equation 32 calculates the volume of concrete required for the mixing tank.

$$\text{Concrete Volume} = 2 * \{\text{Length} * (\text{Depth} + \text{Freeboard}) * \text{Wall}\} + 2 * \{\text{Width} * (\text{Depth} + \text{Freeboard}) * \text{Wall}\} + \{(\text{Length} + \text{Wall}) * (\text{Width} + \text{Wall}) * \text{Bottom}\} \tag{32}$$

Equation 33 calculates the cost of the mixing tank including the excavation and concrete costs.

$$\text{Mixing Tank Cost} = \frac{\text{Excavation Volume}}{\text{CF}_{volume,dry}} * \text{Excavation Unit Cost} + \frac{\text{Concrete Volume}}{\text{CF}_{volume,dry}} * \text{Concrete Unit Cost} \quad (33)$$

Table 4-8 describes the variables in the mixing tank cost section of the hydrated lime cost module shown in equations 28 through 33 and provides the values used in the equations for each effluent scenario.

Table 4-8. Hydrated Lime Mixing Tank Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Bottom	ft	Thickness of the mixing tank bottom	1 ft	*AMDTreat® v.4.1*
$CF_{volume,dry}$	ft^3/yd^3	Conversion factor for converting cubic feet to cubic yards	27 ft^3/yd^3	Constant
$CF_{volume,wet}$	gal/ft^3	Conversion factor for converting gallons to cubic feet	7.4805 gal/ft^3	Constant
Concrete Unit Cost	$/yd^3$	Unit cost for concrete	$ 100/yd^3	*AMDTreat® v.4.1*
Concrete Volume	ft^3	Concrete volume for mixing tank	NA	Calculated in Equation 32
Depth	ft	Depth of mixing tank	NA	Calculated in Equation 30
Excavation Unit Cost	$/yd^3$	Unit cost for excavating	$ 5.5/yd^3	*AMDTreat® v.4.1*
Excavation Volume	ft^3	Excavation volume for mixing tank	NA	Calculated in Equation 31
Flow	gal/min	Discharge flow	Input Parameter	Model Mine Characteristics
Freeboard	ft	Freeboard depth above the mixing tank depth to allow for increases in flow	1 ft	*AMDTreat® v.4.1*
Length	ft	Length of mixing tank	NA	Calculated in Equation 29
Mixing Tank Cost	$	Cost for mixing tank including excavation and concrete costs	NA	Calculated in Equation 33
Retention Time	min	Mixing tank retention time	5 min	*AMDTreat® v.4.1*
Tank Volume	gal	Volume of mixing tank required to mix the hydrated lime with the untreated discharge	NA	Calculated in Equation 28
Wall	ft	Thickness of the mixing tank wall	1 ft	*AMDTreat® v.4.1*
Width	ft	Width of mixing tank	NA	Calculated in Equation 29

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.2.3   Total Capital Costs

The total capital cost includes the cost of the hydrated lime storage silos, mixing tank, hydrated lime control building, and hydrated lime addition control system. This cost module assumes that the hydrated lime control building size and hydrated lime addition system are independent of the number and size of the hydrated lime storage silos and therefore are the same for both effluent scenarios. However, these costs are included for comparison to other cost modules for EPA's Detailed Study of the Coal Mining Industry.

Equation 34 calculates the cost of the hydrated lime control building.

$$\text{Building Cost} = \text{Building Length} * \text{Building Width} * \text{Building Unit Cost} \tag{34}$$

Equation 35 calculates the cost of the hydrated lime control system cost.

$$\begin{aligned}\text{Control Cost} = &\text{ Mixers} * \text{Mixer Cost} + \text{Slide Gates} * \text{Slide Gate Cost} + \text{Electric Panel} + \text{Vibrator Air Sweep} \\ &+ \text{Pneumatic Air Sweep} + \text{Blower Blocks} + \text{Construction Cost}\end{aligned} \tag{35}$$

Equation 36 calculates the total cost of the hydrated lime chemical precipitation system.

$$\text{Total Capital Cost} = \text{Total Silo Cost} + \text{Mixing Tank Cost} + \text{Building Cost} + \text{Control Cost} \tag{36}$$

Table 4-9 describes the variables in the total capital cost section of the hydrated lime cost module shown in equations 34, 35, and 36 and provides the values used in the equations for each effluent scenario.

Table 4-9. Total Capital Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Blower Blocks	$	Cost of blower blocks in the hydrated lime system	$ 0	*AMDTreat® v.4.1*
Building Cost	$	Cost of building that houses the electric control panel and other control equipment	NA	Calculated in Equation 34
Building Length	ft	Length of building that houses the electric control panel and other control equipment	15 ft	*AMDTreat® v.4.1*
Building Unit Cost	$/ft^2	Cost of building on a square footage basis	$ 10/ft^2	*AMDTreat® v.4.1*
Building Width	ft	Width of building that houses the electric control panel and other control equipment	15 ft	*AMDTreat® v.4.1*
Mixing Tank Cost	$	Cost for mixing tank including excavation and concrete costs	NA	Calculated in Equation 33
Construction Cost	$	Cost of constructing the hydrated lime system	$ 6,000	*AMDTreat® v.4.1*
Control Cost	$	Cost of control equipment for the hydrated lime system	NA	Calculated in Equation 35

Table 4-9. Total Capital Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Electric Panel	$	Cost of electric panel to control the hydrated lime system	$ 2,000	*AMDTreat® v.4.1*
Mixer Cost	$/No.	Cost of mixer in the hydrated lime system	$ 1,000	*AMDTreat® v.4.1*
Mixers	No.	Number of mixers in the hydrated lime system	2	*AMDTreat® v.4.1*
Pneumatic Air Sweep	$	Cost of pneumatic air sweep in the hydrated lime system	$ 0	*AMDTreat® v.4.1*
Slide Gate Cost	$/No.	Cost of slide gate valve in the hydrated lime system	$ 750	*AMDTreat® v.4.1*
Slide Gates	No.	Number of slide gate valves in the hydrated lime system	5	*AMDTreat® v.4.1*
Total Capital Cost	$	Total capital cost for hydrated lime system	NA	Calculated in Equation 36
Total Silo Cost	$	Total cost for all silos in treatment system	NA	Calculated in Equation 28
Vibrator Air Sweep	$	Cost of vibrator air sweep in the hydrated lime system	$ 0	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

3.3   Effluent Scenario Cost Comparison

EPA is estimating the cost difference between using chemical precipitation and other treatment technologies to achieve two different effluent scenarios:

1.   To meet all of the 40 CFR Part 434 limits (TSS, pH, iron, and manganese); and
2.   To meet only the TSS, pH, and iron limits in 40 CFR Part 434.

Prior to calculating the cost difference, the capital costs must be annualized for each effluent scenario. Equations 37 and 38 calculate the total annualized costs for the hydrated lime chemical precipitation system.

$$\text{Annualized Capital Cost} = \text{Total Capital Cost} * \frac{\{\text{Interest} * (1 + \text{Interest})^{\text{years}}\}}{(1 + \text{Interest})^{\text{years}} - 1} \tag{37}$$

$$\text{Total Annualized Cost} = \text{Annualized Capital Cost} + \text{Total Annual Cost} \tag{38}$$

Equation 39 compares the total annualized cost for effluent scenario 1 with the total annualized cost for effluent scenario 2.

$$\text{Net Annual Cost} = \text{Total Annualized Cost}_{\text{Effluent Scenario 1}} - \text{Total Annualized Cost}_{\text{Effluent Scenario 2}} \tag{39}$$

Table 4-10 describes the variables in the effluent scenario cost comparison section of the hydrated lime cost module shown in equations 37, 38, and 39 and provides the values used in the equations for each effluent scenario.

Table 4-10. Effluent Scenario Cost Comparison Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annualized Capital Cost	$/yr	Annualized capital cost for hydrated lime treatment system	NA	Calculated in Equation 37
Interest	%	Interest rate for annualization	10 %	EPA
Net Annual Cost	$/yr	Net annual cost to increase from pH 8.3 to pH 10 using hydrated lime treatment system	NA	Calculated in Equation 39
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 15
Total Annualized Cost	$/yr	Total annualized cost (capital and annual) for caustic treatment system	NA	Calculated in Equation 38
Total Capital Cost	$	Total capital cost for the hydrated lime treatment system	NA	Calculated in Equation 36
Years	yr	Years for annualization calculation	75 yr	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.0 REFERENCES

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**Attachment A – *AMDTreat*® *v.4.1* Default Values for Hydrated Lime Chemical
Precipitation Cost Module**

Table A-1. *AMDTreat® v.4.1* **Default Values for the Hydrated Lime Chemical Precipitation Cost Module**

Variable	Variable Description	AMDTreat® v.4.1 Default Value	Equation Reference
% Solids	Ratio of the weight of solids to the weight of water	5 %	4, 5, 6, 7
Blower Blocks	Cost of blower blocks in the hydrated lime system	$ 0	35
Bottom	Thickness of the mixing tank bottom	1 ft	31, 32
Building Length	Length of building that houses the electric control panel and other control equipment	15 ft	34
Building Unit Cost	Cost of building on a square footage basis	$ 10/ft^2	34
Building Width	Width of building that houses the electric control panel and other control equipment	15 ft	34
Collection Time	Average time expected for the worker to collect one sample	0.33 hr	9
Concrete Unit Cost	Unit cost for concrete	$ 100/yd^3	33
Construction Cost	Cost of constructing the hydrated lime system	$ 6,000	35
$Cost_{20}$	Cost of 20 ton silo	$ 25,000	22, 23, 24, 25, 26
$Cost_{35}$	Cost of 35 ton silo	$ 27,000	22, 23, 24, 25, 26
$Cost_{50}$	Cost of 50 ton silo	$ 32,000	22, 23, 24, 25, 26
$Cost_{60}$	Cost of 60 ton silo	$ 35,000	22, 23, 24, 25, 26
$Density_{Sludge}$	Density of solids and water in sludge	8.33 lb/gal	4, 5, 6, 7
Efficiency	Mixing efficiency of hydrated lime with discharge	80 %	2
Electric Panel	Cost of electric panel to control the hydrated lime system	$ 2,000	35
Excavation Unit Cost	Unit cost for excavating	$ 5.5/yd^3	33
Freeboard	Freeboard depth above the mixing tank depth to allow for increases in flow	1 ft	31, 32
Hydrated Lime Cost	Cost of hydrated lime	$ 0.10/lb	3
Labor Cost	Hourly rate for worker	$ 35.00/hr	9, 10, 13
Labor Time	Time expected for worker to inspect the treatment system and ensure it's working correctly	2 hr	13
Mixer Cost	Cost of mixer in the hydrated lime system	$ 1,000	35
Mixers	Number of mixers in the hydrated lime system	2	35
Monthly Frequency	Number of samples collected per month	2/month	9, 10, 11
Pneumatic Air Sweep	Cost of pneumatic air sweep in the hydrated lime system	$ 0	35
Purity	Purity of hydrated lime	96 %	2
Removal Cost	Cost of removing sludge	$ 0.06/gal	8
Retention Time	Mixing tank retention time	5 min	28
Sample Cost	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	11
Sampling Points	Number of sampling points in treatment system	3	9, 11

Table A-1. *AMDTreat® v.4.1* **Default Values for the Hydrated Lime Chemical Precipitation Cost Module**

Variable	Variable Description	*AMDTreat® v.4.1* Default Value	Equation Reference
Slide Gate Cost	Cost of slide gate valve in the hydrated lime system	$ 750	35
Slide Gates	Number of slide gate valves in the hydrated lime system	5	35
Travel Time	Time expected for worker to travel from the office to the site	2 hr	10, 13
Vibrator Air Sweep	Cost of vibrator air sweep in the hydrated lime system	$ 0	35
Wall	Thickness of the mixing tank wall	1 ft	31, 32

Source: *AMDTreat® v.4.1*.

Appendix D

DRAFT ACID MINE DRAINAGE TREATMENT COST MODULE: LIMESTONE BED

Draft Acid Mine Drainage Treatment Cost Module:
Limestone Bed
August 16, 2007

Disclaimer: This is a <u>draft</u> module. EPA developed this module for the Detailed Study of the Coal Mining Point Source Category (40 CFR Part 434) to estimate the cost difference between treating acid mine drainage (AMD) using a limestone bed over a range of flows:

- To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
- To meet only the TSS, pH, and iron limitations in 40 CFR Part 434.

The costs are based on calculations and default values provided in the *AMDTreat*® software that was developed cooperatively by the Pennsylvania Department of Environmental Protection (PA DEP), West Virginia Department of Environmental Protection (WV DEP), and the U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE) (OSMRE, 2007a). The default values from *AMDTreat*® that are used in the limestone bed cost module are presented in Attachment A (OSMRE, 2007b).

OSMRE reviews and updates the treatment costs roughly annually. The most recent version of *AMDTreat*®, version 4.1, expresses costs in 2006 dollars. *AMDTreat*® *v.4.1* has not been peer reviewed (Wolford, 2007a).

1.0   MODULE METHODOLOGY

This module estimates the costs associated with installing and operating a limestone bed treatment system for treatment of AMD. Limestone beds are used to neutralize acidity and precipitate metal ions in AMD. EPA is estimating the cost difference between using a limestone bed to achieve two different effluent scenarios:

1.   To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
2.   To meet only the TSS, pH, and iron limitations of 40 CFR Part 434.

40 CFR Part 434 defines AMD as mine drainage that, before treatment, either has a pH of less than 6.0 or a total iron concentration equal to or greater than 10 mg/L. The limitations for AMD are in 40 CFR Part 434 Subpart C, shown in Table 1-1 (BAT) and Table 1-2 (NSPS). The best available technology economically achievable (BAT) limitations apply to coal mines that were constructed prior to May 4, 1984. The new source performance standards (NSPS) limitations apply to coal mines that were constructed after May 4, 1984. EPA assumes the majority of the coal mines are required to meet the NSPS limitations and will use the NSPS limitations presented in Table 1-2 for the effluent scenarios.

Table 1-1. BAT Effluent Guidelines for Coal Mining Part 434, Subpart C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.5	7.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.
[a]Subpart C – Acid or Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Point Source Category.

Table 1-2. NSPS Effluent Guidelines for Coal Mining Part 434, Subpart C[a]

Parameter	30-day Average (mg/L)	Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70
pH	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0
Manganese, Total	2.0	4.0

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
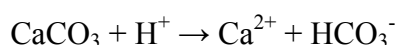NA – Not applicable.
[a]Subpart C – Acid or Ferruginous Mine Drainage applies to coal mines in EPA's Detailed Study of the Coal Mining Point Source Category.

Under the first effluent scenario, EPA estimates the costs to remove pollutants to meet all the NSPS limitations in Table 1-2. Under the second effluent scenario, EPA estimates the costs to remove all pollutants except manganese to the NSPS limitations level required by 40 CFR Part 434 presented in Table 1-2.

2.0 PROCESS DESCRIPTION

Limestone beds are one of many "passive treatment systems" used in the coal mining industry to meet the 40 CFR Part 434 permit limits. Limestone beds are trenches filled with limestone for AMD treatment by precipitating metals and increasing alkalinity. Figure 2-1 shows a typical limestone bed treatment system process.

The limestone bed is designed to 1) increase alkalinity and raise pH to neutral (between 6 and 9) and 2) precipitate and remove metals from the AMD. As limestone dissolves, it imparts alkalinity according to the following reactions (Sibrell, 2005):

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$$

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2\ HCO_3^-$$

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^-$$

The available hydroxide ions (OH^-) then react with metals to form insoluble metal hydroxides, which form according to the following equations:

$$Metal^{+2} + 2\ OH^- \rightarrow Metal(OH)_2$$

$$Metal^{+3} + 3\ OH^- \rightarrow Metal(OH)_3$$
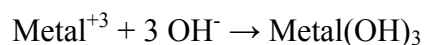
The insoluble metal hydroxides will precipitate and be removed from the water; however, over time the precipitates coat the limestone. This coating of the limestone is referred to as "armoring" and will decrease the effectiveness of the limestone bed over time. High flow velocities through the bed can minimize the armoring, and the limestone beds should be made large enough to account for armoring.

As the metal cations, such as Fe^{3+} and Mn^{2+}, consume the hydroxide anions in the above reactions, the pH of the water will decrease. To be effective, limestone beds should be large enough to buffer the acidity liberated from metals precipitation.

Some types of AMD are not suitable for treatment with a limestone bed. For example, limestone beds receiving AMD with high metals concentrations will likely become armored very quickly compared to those receiving AMD with a low pH but lower metals concentrations. In addition, a pH of 10 is required to quickly precipitate certain metals such as manganese and zinc (Means, 2004).

Often sites will add lime or caustic following a limestone bed to adjust pH to 10. Limestone beds can achieve removal of metals such as manganese and zinc, if sufficient residence time and buffering capacity are provided. In some cases, the bed size required to achieve such residence time is impractical. Figure 2-2 illustrates the solubility curves from research performed by Dr. Chuck Cravotta, U.S.G.S. for metals commonly in AMD, showing solubilities relative to pH (Means, 2004). This figure demonstrations just one of the reasons why limestone beds must be sized larger for manganese treatment.

The buffering capacity needed to maintain a neutral pH for AMD can be estimated by calculating the total acidity of the AMD: the acidity from pH as well as the acidity liberated from metals precipitating as insoluble hydroxides. For this cost module, EPA attempts to quantify the difference in buffering capacity needed to achieve the following:

1. Maintain a neutral pH and allow for a long enough residence time such that iron and manganese precipitate, resulting in concentrations meeting 40 CFR Part 434 limits; and
2. Maintain a neutral pH and allow for a long enough residence time such that iron precipitates, resulting in concentrations meeting 40 CFR Part 434 limits.

Many scientists have studied how to best measure acidity in AMD. Two studies in particular address EPA's question of the differing buffer capacities required to 1) treat iron and

manganese to meet the 40 CFR Part 434 limits and 2) treat solely iron to meet the 40 CFR Part 434 limits.

- Kirby and Cravotta: Net Alkalinity and Net Acidity 1: Theoretical Considerations (Kirby, 2005a) and Net Alkalinity and Net Acidity 2: Practical Considerations (Kirby, 2005b). Attachment B contains these articles.
- Means and Hilton: Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage (Means, 2004). Attachment C contains this article.

While scientists have found that iron will precipitate quickly at a pH near 7, manganese reacts more slowly and requires a longer residence time within the limestone bed to precipitate (Means, 2004). The slower manganese reaction time is a function of several factors, including solubility.
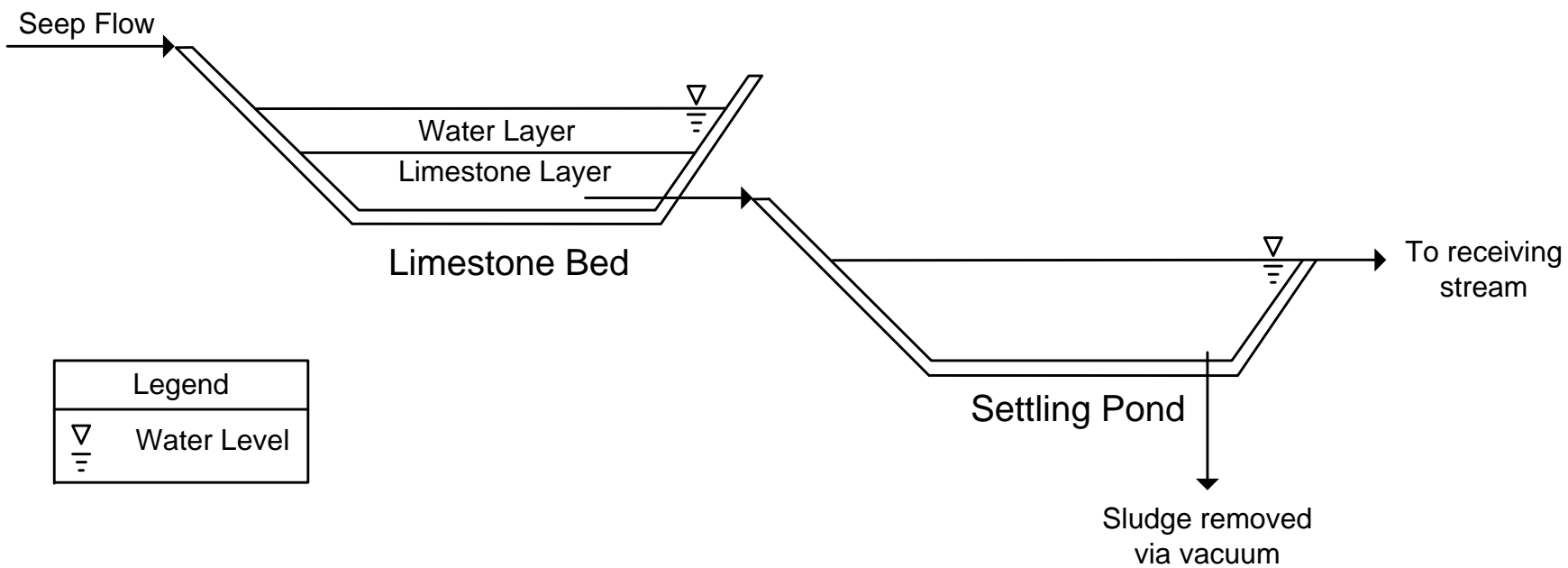
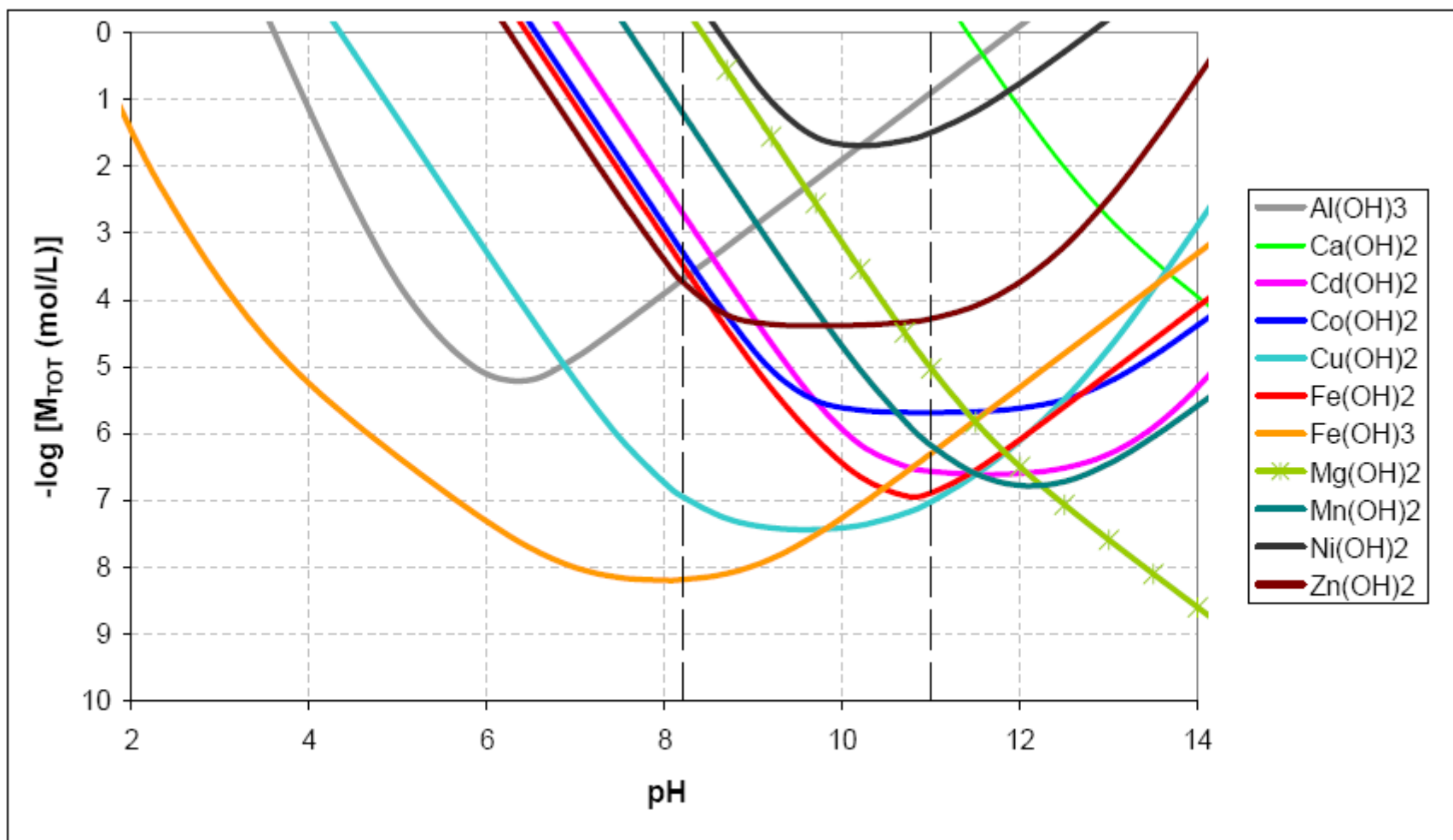**Figure 2-1. Example AMD Limestone Bed Treatment System**

Figure 2-2. Comparison of Metal Hydroxide Solubilities for Constituents Commonly Found in Acidic Mine Drainage (Means, 2004)

3.0   DESIGN CONSIDERATIONS

This cost module considers the costs required for a limestone bed. EPA is estimating the cost of treating AMD with chemical precipitation using caustic soda and lime in separate cost modules (see "Draft Acid Mine Drainage Treatment Cost Module: Chemical Precipitation Using Caustic Soda" and "Draft Acid Mine Drainage Treatment Cost Module: Chemical Precipitation Using Hydrated Lime" both dated August 2007 (see Appendices C and D)). For limestone beds, EPA considered the amount of limestone needed to buffer the pH for the necessary residence time, the surface area disturbed and the required operating labor.

EPA assumes that annual cost for electricity and land requirements are approximately equal under both effluent scenarios. For this reason, EPA did not consider the cost of obtaining or leasing land for the treatment system or other capital equipment costs or electricity needs in its estimate of annual costs.[1]

4.0   COST MODULE CALCULATIONS

EPA is estimating costs to treat AMD with a limestone bed to achieve two different effluent scenarios:

1. To meet all of the 40 CFR Part 434 limitations (TSS, pH, iron, and manganese); and
2. To meet only the TSS, pH, and iron limitations of 40 CFR Part 434.

Table 4-1 presents the limits for each of the effluent scenarios. The difference between the effluent scenarios is that effluent scenario 1 meets the current manganese limits while effluent scenario 2 does not incorporate any change in manganese concentration. For calculation purposes, only the 30-day limit is considered, because it is lower than the daily maximum limit.

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[1] For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, the land acquisition or lease costs were not included in the Limestone Bed Cost Module. Although these costs may affect the estimated difference, or net delta, in costs for the limestone bed technology to meet effluent scenario 1 versus effluent scenario 2, EPA does not have sufficient information at this time to estimate the land acquisition or lease costs. EPA requests input and would consider any comments on how to incorporate these costs into the limestone bed cost module.

Table 4-1. Effluent Discharge Limitations for Effluent Scenarios

Parameter	Effluent Scenario 1		Effluent Scenario 2	
	NSPS 30-Day Average (mg/L)	NSPS Daily Maximum (mg/L)	NSPS 30-day Average (mg/L)	NSPS Daily Maximum (mg/L)
Total Suspended Solids (TSS)	35	70	35	70
pH	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9	within range of 6 to 9
Iron, Total	3.0	6.0	3.0	6.0
Manganese, Total	2.0	4.0	NA	NA

Source: *Development Document for Effluent Limitations Guidelines and Standards for the Coal Mining Point Source Category* (U.S. EPA, 1982).
NA – Not applicable.

The first effluent scenario will be achieved by allowing for sufficient residence time in the limestone bed to neutralize all of the acidity from pH, iron, aluminum, manganese, and other ions that will consume alkalinity, such as magnesium. (Sibrell, 2005) EPA assumes that if the limestone bed neutralizes the acidity from these components, the effluent quality will be:[2]

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

The second effluent scenario will be achieved by allowing for sufficient residence time in the limestone bed to neutralize all of the acidity from pH, iron, and aluminum and part of the acidity resulting from manganese and other ions such as magnesium. (Sibrell, 2005) EPA assumes that if the limestone bed neutralizes the acidity from these components, the effluent quality will be:[3]

- Iron at 3.0 mg/L;
- A 10 percent reduction in manganese from untreated;
- A 99 percent reduction in aluminum from untreated; and
- No reduction in magnesium from untreated.

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[2] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.
[3] Ibid.

Thus, the difference in required residence time between the first effluent scenario and the second effluent scenario is the acidity resulting from the precipitation of manganese and other ions, such as magnesium (Sibrell, 2005).

For both effluent scenarios the cost module includes the following items:

- Capital Costs (Section 4.1) including:
  — Limestone cost (Section 4.1.1);
  — Excavation cost (Section 4.1.2);
  — Liner cost (Section 4.1.3).

- Annual Costs (Section 4.2) including;
  — Sludge removal cost (Section 4.2.1);
  — Limestone turning cost (Section 4.2.2);
  — Sampling cost (Section 4.2.3);
  — Maintenance labor cost (Section 4.2.4).

The sampling cost and maintenance labor costs will be the same for each effluent scenario because these portions of the cost module do not depend on effluent water characteristics. Therefore, the sampling cost and maintenance labor cost for each effluent scenario will off-set when the total costs are compared. However, these costs are included for comparison to other costing modules in EPA's Detailed Study of the Coal Mining Point Source Category.

4.1   Capital Costs

The following sections describe the calculation of capital costs.

4.1.1   Limestone Cost

Under the first effluent scenario, EPA is estimating the cost of limestone for a limestone bed to buffer the acidity from pH, iron, aluminum, manganese, and other ions that will consume alkalinity, such as magnesium. EPA assumes that by buffering the acidity from these components, the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) and manganese (2 mg/L 30-day average) limitations. This assumption is based on the typical buffering capacity of limestone: 0.4 to 40 gal/day/ton of limestone (Skousen, 2005). Under the second effluent scenario, EPA is estimating the cost of limestone for a limestone bed to buffer acidity from pH, iron, aluminum, and some acidity from manganese and other ions. EPA assumes that by buffering the acidity from these components, the effluent will meet the 40 CFR Part 434 NSPS iron (3 mg/L 30-day average) limitation but will not meet the manganese (2 mg/L 30-day average) limitation (Skousen, 2005).[4]

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[4] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumptions that 1) a multiplier of 4 accounts for the additional acidity liberated when raising pH to 10 to settle manganese and 2) that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. 1) Mine drainage chemistry is complex and variable. In some AMD, as demonstrated in *Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004), there may be little additional acidity

The amount of limestone required for the limestone bed depends on:

- Net acidity;
- Discharge flow rate;
- System life; and
- The additional acidity required to increase the pH to the desired level.

The net acidity is estimated based on pH, metals concentrations (specifically ferrous and ferric iron, manganese, and aluminum), additional acidity liberated to achieve pH 10, and alkalinity. Equation 1 calculates the net acidity.

$$\text{Net Acidity} = 50*\{(1000*10^{-pH}) + \frac{2*Fe^{2+}+3*Fe^{3+}}{55.842} + \frac{2*Mn}{54.93807} + \frac{3*Al}{26.9815386}\} * \text{Acidity Multiplier} - \text{Alkalinity} \qquad (1)$$

where:
- Acidity Multiplier. A factor accounting for additional acidity liberated to achieve pH 10;
- Net acidity. Laboratory-measured acidity; and
- Alkalinity. Laboratory-measured alkalinity.

The acidity multiplier is derived from the Means and Hilton article entitled "Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage," in Attachment C. The scientists found that the Standard Method (SM) 2310 for hot acidity is often not a valid expression of acidity for waters with pH's greater than 8.2. The article concludes that when adding caustic to adjust pH for manganese precipitation (i.e., to increase the pH to 10), plant operators must consider the amount of caustic consumed by magnesium and other ions. The amount of caustic consumed by magnesium and other ions at pH's above 10 is not accounted for by SM 2310. The additional caustic required to change the pH from 8.3 to 10 represents the additional buffering capacity required to neutralize the acidity liberated by the precipitation of manganese and other ions.

As a result, EPA used data from the Means and Hilton article to estimate the additional buffering capacity needed when adjusting pH above 8.3. Means and Hilton provide data for four different discharges of AMD (Means, 2004). EPA selected the "worst case scenario," or the data for the AMD requiring the greatest additional buffering capacity to increase the pH to 10, for manganese removal. The data demonstrate that to adjust pH from 8.3 to 10, roughly three times the amount of buffering capacity is necessary, and the acidity multiplier is 4.

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liberated when titrating pH to 10. For AMD with these characteristics, the multiplier of 4 overestimates the amount of treatment chemical required to adjust pH for manganese treatment. 2) Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron.

The amount of limestone required to achieve a specific pH is based on the net acidity, discharge flow rate, mixing efficiency, and limestone purity. Equation 2 calculates the amount of limestone required to achieve a specific pH (pH 10 for effluent scenario 1 and pH 8.3 for effluent scenario 2).

$$\text{Limestone}_{Mass} = \text{Flow} * \text{Net Acidity} * \text{System Life} * \frac{CF_{time}}{CF_{weight,1}} * CF_{volume,1} * \frac{1}{\text{Purity}} * \frac{1}{\text{Efficiency}} \tag{2}$$

Equation 3 calculates the cost of limestone required to achieve the desired pH for the life of the limestone bed treatment system.

$$\text{Limestone Cost} = \text{Limestone}_{Mass} * \frac{\text{Limestone Unit Cost}}{\text{Density}} + \frac{\text{Limestone}_{Mass}}{CF_{volume,2}} * \text{Limestone Placement Cost} * CF_{weight,2} \tag{3}$$

Table 4-1 describes the variables in the limestone cost section of the limestone bed cost module shown in Equations 1 through 3 and provides the values used in the equations for each effluent scenario.

Table 4-1. Limestone Cost Variable Description

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Acidity Multiplier	None	Multiplier of additional acidity liberated when increasing the pH from 8.3 to 10 and additional acidity represents the alkalinity consumed by precipitation of manganese	4	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	0	*Net Alkalinity and Net Acidity* Papers (Kirby, 2005a; Kirby, 2005b)
Al	mg/L	Aluminum concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Alkalinity	mg $CaCO_3$/L	Alkalinity in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
CF_{time}	min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
$CF_{volume, 1}$	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
$CF_{volume, 2}$	ft^3/yd^3	Conversion factor for converting cubic feet to cubic yards	27 ft^3/yd^3	Constant	27 ft^3/yd^3	Constant
$CF_{weight, 1}$	mg/ton	Conversion factor for converting milligrams to tons	9.08×10^8 mg/ton	Constant	9.08×10^8 mg/ton	Constant
$CF_{weight, 2}$	lb/ton	Conversion factor for converting pounds to tons	2,000 lb/ton	Constant	2,000 lb/ton	Constant
Density	lb/ft^3	Density of loose limestone in the limestone bed as delivered to the site including void space	94.3 lb/ft^3	*AMDTreat® v.4.1*	94.3 lb/ft^3	*AMDTreat® v.4.1*
Efficiency	%	Efficiency of limestone at imparting alkalinity	60 %	*AMDTreat® v.4.1*	60 %	*AMDTreat® v.4.1*
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics

Table 4-1. Limestone Cost Variable Description

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Flow	gpm	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$Limestone_{Mass}$	ton	Amount of limestone to achieve desired pH	NA	Calculated in Equation 2	NA	Calculated in Equation 2
Limestone Cost	$	Cost of limestone required to achieve desired pH	NA	Calculated in Equation 3	NA	Calculated in Equation 3
Limestone Placement Cost	$/yd^3	Cost of placing the limestone into the limestone bed	$ 2/yd^3	*AMDTreat® v.4.1*	$ 2/yd^3	*AMDTreat® v.4.1*
Limestone Unit Cost	$/ton	Cost of limestone	$ 22/ton	*AMDTreat® v.4.1*	$ 22/ton	*AMDTreat® v.4.1*
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Net Acidity	mg CaCO$_3$/L	Discharge net acidity	NA	Calculated in Equation 1	NA	Calculated in Equation 1
pH	standard units	Untreated discharge pH	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Purity	% (mg CaCO$_3$/ 100 mg limestone)	Purity of limestone	85 %	*AMDTreat® v.4.1*	85 %	*AMDTreat® v.4.1*
System Life	years	Years the limestone bed treatment system must last	75 years	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)	75 years	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)

[a]Effluent Scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent Scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.2 Excavation Costs

The required excavation volume depends on the required limestone mass (Limestone$_{Mass}$) and the shape of the limestone bed. The excavation is only necessary for the limestone and water layers because EPA assumes the excavated soil will be used to create a berm around the limestone bed for the freeboard volume.

Equation 4 estimates the volume of limestone required to achieve the desired effluent pH, based on the limestone mass from equation 2.

$$\text{Limestone Volume} = \frac{\text{Limestone}_{Mass}}{\text{Density}} * CF_{weight} \qquad (4)$$

EPA assumed the limestone bed shape is a prismatoid following *AMDTreat® v.4.1*'s conventions. Figures 4-1 and 4-2 present the dimensions on a limestone bed.
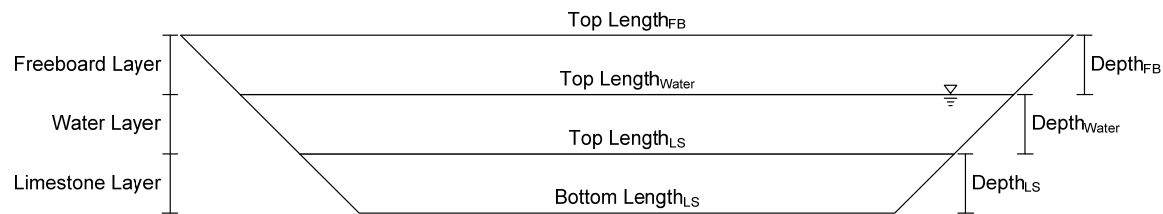

Figure 4-1. Side-View of Limestone Bed with Dimensions

Figure 4-2. End-View of Limestone Bed with Dimensions

Equations 5 through 8 can be used to calculate the dimensions of the limestone bed. These equations are taken from the *AMDTreat® v.4.1* Help Guide.

$$\text{Top Width}_{LS} = \frac{3 * \text{Depth}_{LS}}{4 * \text{Slope}} + \left\{\frac{-5 * (\text{Depth}_{LS})^2}{48 * (\text{Slope})^2} + \frac{0.5 * \text{Limestone Volume}}{\text{Depth}_{LS}}\right\}^{1/2} \qquad (5)$$

$$\text{Top Length}_{LS} = 2 * \text{Top Width}_{LS} \qquad (6)$$

$$\text{Top Width}_{Water} = \text{Top Width}_{LS} + \frac{2 * \text{Depth}_{Water}}{\text{Slope}} \qquad (7)$$

$$\text{Top Length}_{Water} = \text{Top Length}_{LS} + \frac{2 * \text{Depth}_{Water}}{\text{Slope}} \qquad (8)$$

Equation 9 calculates the volume of the water in the limestone bed based on the dimensions of the limestone and water layers of the limestone bed.

$$\text{Water Volume} = \text{Top Width}_{Water} * \text{Top Length}_{Water} + 4 * (\text{Top Length}_{Water} - \frac{\text{Depth}_{Water}}{\text{Slope}}) \tag{9}$$

$$* (\text{Top Width}_{Water} - \frac{\text{Depth}_{Water}}{\text{Slope}}) + \frac{\text{Width}_{LS} * \text{Length}_{LS} * \text{Depth}}{6}$$

Equation 10 calculates the excavation cost based on the limestone and water volumes. The freeboard is not included in the excavation volume because *AMDTreat® v.4.1* assumes that the excavated volume will be used to create a berm around the limestone bed f or the freeboard volume.

$$\text{Excavation Cost} = (\text{Limestone Volume} + \text{Water Volume}) * \frac{\text{Excavation Unit Cost}}{\text{CF}_{volume}} \tag{10}$$

Table 4-2 describes the variables in the excavation cost section of the limestone bed cost module shown in Equations 5 through 10 and provides the values used in the equations for each effluent scenario.

Table 4-2. Excavation Cost Variable Description

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
CF_{volume}	ft^3/yd^3	Conversion factor for converting cubic feet to cubic yards	$27\ ft^3/yd^3$	Constant	$27\ ft^3/yd^3$	Constant
CF_{weight}	lb/ton	Conversion factor for converting pounds to tons	2,000 lb/ton	Constant	2,000 lb/ton	Constant
Density	lb/ft^3	Density of loose limestone in the limestone bed as delivered to the site including void space	$94.3\ lb/ft^3$	*AMDTreat® v.4.1*	$94.3\ lb/ft^3$	*AMDTreat® v.4.1*
$Depth_{LS}$	ft	Depth of limestone in limestone bed	3 ft	*AMDTreat® v.4.1*	3 ft	*AMDTreat® v.4.1*
$Depth_{Water}$	ft	Depth of water in the limestone bed	2 ft	*AMDTreat® v.4.1*	2 ft	*AMDTreat® v.4.1*
Excavation Cost	$	Cost of excavating soil for the limestone bed	NA	Calculated in Equation 10	NA	Calculated in Equation 10
Excavation Unit Cost	$/yd^3$	Cost of excavating	$ 5.5/yd^3$	*AMDTreat® v.4.1*	$ 5.5/yd^3$	*AMDTreat® v.4.1*
Top Length$_{LS}$	ft	Length of limestone bed at the top of the limestone	NA	Calculated in Equation 6	NA	Calculated in Equation 6
Top Length$_{Water}$	ft	Length of limestone bed at the top of the water layer	NA	Calculated in Equation 8	NA	Calculated in Equation 8
Limestone	ton	Amount of limestone to achieve desired pH	NA	Calculated in Equation 2	NA	Calculated in Equation 2
Limestone Volume	ft^3	Volume of limestone based on the amount of limestone required to achieve the desired pH	NA	Calculated in Equation 4	NA	Calculated in Equation 4
Slope	None	Slope of the sides of the limestone bed	0.5	*AMDTreat® v.4.1*	0.5	*AMDTreat® v.4.1*
Water Volume	ft^3	Volume of water in the limestone bed	NA	Calculated in Equation 9	NA	Calculated in Equation 9

Table 4-2. Excavation Cost Variable Description

Variable	Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Top Width$_{LS}$	ft	Width of limestone bed at the top of the limestone	NA	Calculated in Equation 5	NA	Calculated in Equation 5
Top Width$_{Water}$	ft	Width of limestone bed at the top of the water layer	NA	Calculated in Equation 7	NA	Calculated in Equation 7

[a]Effluent Scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent Scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.3   Liner Cost

The limestone bed is lined with either a clay or synthetic liner. EPA calculated the cost of both liners. The liner cost is based on the surface area of the bottom and sides of the limestone bed. The surface area depends on the dimensions of the limestone bed.

Equations 11 through 14 calculates additional dimensions of the limestone bed.

$$\text{Bottom Width}_{LS} = \text{Top Width}_{LS} - \frac{2 * \text{Depth}_{LS}}{\text{Slope}} \tag{11}$$

$$\text{Bottom Length}_{LS} = \text{Top Length}_{LS} - \frac{2 * \text{Depth}_{LS}}{\text{Slope}} \tag{12}$$

$$\text{Top Width}_{FB} = \text{Top Width}_{Water} + \frac{2 * \text{Depth}_{FB}}{\text{Slope}} \tag{13}$$

$$\text{Top Length}_{FB} = \text{Top Length}_{Water} - \frac{2 * \text{Depth}_{FB}}{\text{Slope}} \tag{14}$$

Equations 15 and 16 calculates the surface area of the limestone bed based on various dimensions of the limestone bed.

$$\text{Surface Area} = \{(\text{Top Length}_{FB} + \text{Bottom Length}_{LS} + \text{Top Width}_{FB} + \text{Bottom Width}_{LS}) * \frac{(\text{Depth}_{Total})^2}{\text{Slope}} \tag{15}$$
$$+ \frac{(\text{Depth}_{Total})^2}{\text{Slope}}\}^{1/2} + \text{Bottom Width}_{LS} * \text{Bottom Length}_{LS}$$

Where:

$$\text{Depth}_{Total} = \text{Depth}_{LS} + \text{Depth}_{Water} + \text{Depth}_{FB} \tag{16}$$

Equation 17 calculates the cost of a clay liner for the limestone bed based on the limestone bed surface area and clay thickness.

$$\text{Clay Liner Cost} = \frac{\text{Surface Area}}{\text{CF}_{volume}} * \text{Thickness} * \text{Clay Liner Unit Cost} \tag{17}$$

Equation 18 calculates the cost of a synthetic liner for the limestone bed based on the limestone bed surface area.

$$\text{Synthetic Liner Cost} = \frac{\text{Surface Area}}{\text{CF}_{area}} * \text{Synthetic Liner Unit Cost} \tag{18}$$

Table 4-3 describes the variables in the limestone bed liner cost section of the limestone bed cost module shown in Equations 11 through 18 and provides the values used in the equations for each effluent scenario.

Table 4-3. Liner Cost Variable Description

Variable	Units	Variable Description	Effluent Scenarios 1[a] and 2[b]	
			Value	Value Source
Bottom Width$_{LS}$	ft	Width of limestone bed at the bottom of the limestone layer	NA	Calculated in Equation 11
Bottom Length$_{LS}$	ft	Length of limestone bed at the bottom of the limestone layer	NA	Calculated in Equation 12
CF$_{area}$	ft^2/yd^2	Conversion factor for converting square feet to square yards	9 ft^2/yd^2	Constant
CF$_{volume}$	ft^3/yd^3	Conversion factor for converting cubic feet to cubic yards	27 ft^3/yd^3	Constant
Clay Liner Cost	$	Cost of clay liner	NA	Calculated in Equation 17
Clay Liner Unit Cost	$/yd^3	Unit cost of clay liner	$ 5/yd^3	*AMDTreat® v.4.1*
Depth$_{FB}$	ft	Depth of freeboard in the limestone bed	3 ft	*AMDTreat® v.4.1*
Depth$_{LS}$	ft	Depth of limestone in limestone bed	3 ft	*AMDTreat® v.4.1*
Depth$_{Total}$	ft	Total depth of the limestone bed	NA	Calculated in Equation 16
Depth$_{Water}$	ft	Depth of water layer in the limestone bed	2 ft	*AMDTreat® v.4.1*
Slope	None	Slope of the sides of the limestone bed	0.5	*AMDTreat® v.4.1*
Surface Area	ft^2	Surface area of the limestone bed including the limestone, water, and freeboard layers	NA	Calculated in Equation 15
Synthetic Liner Cost	$	Cost of synthetic liner	NA	Calculated in Equation 18
Synthetic Liner Unit Cost	$/yd^2	Unit cost of synthetic liner	$ 5.50/yd^2	*AMDTreat® v.4.1*
Thickness	ft	Clay liner thickness	0.5 ft	*AMDTreat® v.4.1*
Top Length$_{FB}$	ft	Length of limestone bed at the top of the freeboard layer	NA	Calculated in Equation 14
Top Length$_{Water}$	ft	Length of limestone bed at the top of the water layer	NA	Calculated in Equation 8
Top Width$_{FB}$	ft	Width of limestone bed at the top of the freeboard layer	NA	Calculated in Equation 13
Top Width$_{LS}$	ft	Width of limestone bed at the top of the limestone layer	NA	Calculated in Equation 5
Top Width$_{Water}$	ft	Width of limestone bed at the top of the water layer	NA	Calculated in Equation 7

[a]Effluent Scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent Scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.4   Piping Cost

The limestone bed has piping below the limestone layer to convey treated water out of the limestone bed. This minimizes the amount of insoluble metal hydroxides that precipitate in the limestone bed. The piping costs in the limestone bed module includes the trunk pipe, trunk pipe couplers, spur pipe, spur couplers, "T" connectors, and labor. Figure 4-1 presents the piping layout in the limestone bed.
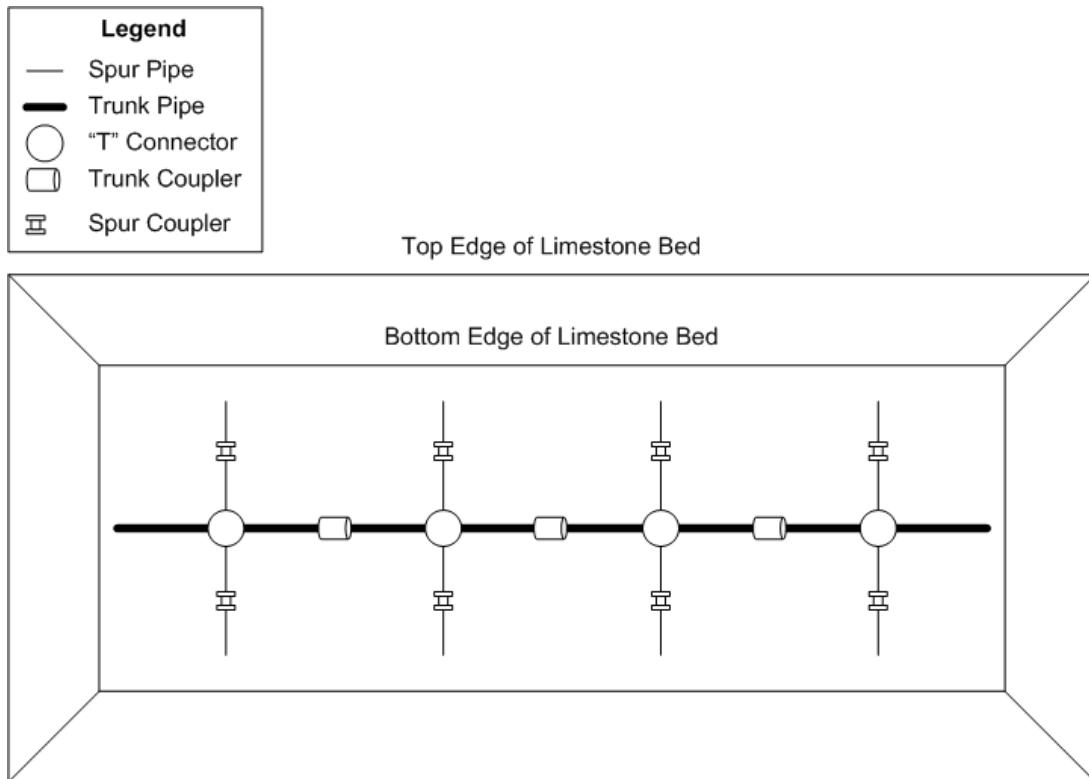

Figure 4-1. Limestone Bed Piping Layout

Equations 19 through 24 calculate the cost of the piping, pipe connectors, and labor to install the piping. The term "Roundup{equation, 0}" represents the number of pipe segments that will need purchased because partial segments are not available. For example, if a segment is 20 feet and the length required by the limestone bed is 45 feet, three segments must be purchased.

$$\text{Trunk Pipe Cost} = \text{Roundup}\left\{\frac{\text{Bottom Length}_{LS} + \text{E/I Pipe}}{\text{Length}_{Trunk}}, 0\right\} * \text{Length}_{Trunk} * \text{Trunk Pipe Unit Cost} \tag{19}$$

$$\text{Trunk Coupler Cost} = \left\{\text{Roundup}\left\{\frac{\text{Bottom Length}_{LS} + \text{E/I Pipe}}{\text{Length}_{Trunk}}, 0\right\} - 1\right\} * \text{Trunk Coupler Unit Cost} \tag{20}$$

$$\text{Spur Pipe Cost} = \text{Roundup}\left\{\frac{\text{Bottom Length}_{LS}}{\text{Spur Spacing}}, 0\right\} * \text{Roundup}\left\{\frac{\text{Bottom Width}_{LS}}{\text{Length}_{Spur}}, 0\right\} * \text{Length}_{Spur} * \text{Spur Unit Cost} \tag{21}$$

Spur Coupler Cost={Roundup{$\underline{Bottom\ Width_{LS}}$, 0}−1}*Roundup{$\underline{Bottom\ Length_{LS}}$, 0}*Spur Coupler Unit Cost (22)
Length$_{Spur}$ Spur Spacing

"T" Connector Cost = Roundup{$\underline{Bottom\ Length_{LS}}$, 0} * Roundup{$\underline{Bottom\ Length_{LS}}$, 0} * Length$_{Spur}$ (23)
Length$_{Spur}$ Spur Spacing
+ Roundup{$\underline{E/I\ Pipe + Bottom\ Length_{LS}}$, 0} * Length$_{Trunk}$ * $\underline{Labor\ Rate}$
Length$_{Trunk}$ Install Rate

Labor Cost = {Roundup{$\underline{Bottom\ Width_{LS}}$, 0} * Roundup{$\underline{Bottom\ Length_{LS}}$, 0} * Length$_{Spur}$ (24)
Length$_{Spur}$ Spur Spacing
+ Roundup{$\underline{E/I\ Pipe + Bottom\ Length_{LS}}$, 0} * Length$_{Trunk}$} * $\underline{Labor\ Rate}$
Length$_{Trunk}$ Install Rate

Piping Cost = Trunk Pipe Cost + Trunk Coupler Cost + Spur Pipe Cost + Spur Coupler Cost (25)
+ "T" Connector Cost + Labor Cost

Table 4-4 describes the variables in the piping cost section of the limestone bed cost module shown in Equations 19 through 25 and provides the values used in the equations for each effluent scenario.

Table 4-4. Piping Cost Variable Description

Variable	Units	Variable Description	Effluent Scenarios 1[a] and 2[b]	
			Value	Value Source
"T" Connector Cost	$	Cost of "T" connector that connects the spur pipe and trunk pipe	NA	Calculated in Equation 23
Bottom Length$_{LS}$	ft	Length of limestone bed at the bottom of the limestone layer	NA	Calculated in Equation 12
Bottom Width$_{LS}$	ft	Width of limestone bed at the bottom of the limestone layer	NA	Calculated in Equation 11
E/I Pipe	ft	Length of effluent and influent pipe to the limestone bed	20 ft	*AMDTreat® v.4.1*
Install Rate	ft/hr	Pipe installation rate	11 ft/hr	*AMDTreat® v.4.1*
Labor Cost	$	Labor cost to install the piping	NA	Calculated in Equation 24
Labor Rate	$/hr	Cost of labor	$ 35/hr	*AMDTreat® v.4.1*
Length$_{Spur}$	ft	Length of spur pipe segment	20 ft	*AMDTreat® v.4.1*
Length$_{Trunk}$	ft/segment	Length of a trunk pipe segment	20 ft/segment	*AMDTreat® v.4.1*
Piping Cost	$	Total cost of piping	NA	Calculated in Equation 25
Spur Coupler Cost	$	Cost of couplers for the spur pipe segments	NA	Calculated in Equation 22
Spur Coupler Unit Cost	$/coupler	Unit cost of coupler for the spur pipe segments	$ 3/coupler	*AMDTreat® v.4.1*

Table 4-4. Piping Cost Variable Description

Variable	Units	Variable Description	Effluent Scenarios 1[a] and 2[b]	
			Value	Value Source
Spur Pipe Cost	$	Cost of spur pipe	NA	Calculated in Equation 21
Spur Spacing	ft	Spacing between spur segments	10 ft	*AMDTreat® v.4.1*
Spur Unit Cost	$/ft	Unit cost of spur pipe	$ 7/ft	*AMDTreat® v.4.1*
Trunk Coupler Cost	$	Cost of couplers for the trunk pipe segments	NA	Calculated in Equation 20
Trunk Coupler Unit Cost	$/coupler	Unit cost of coupler for the trunk pipe segments	$ 6.6/coupler	*AMDTreat® v.4.1*
Trunk Pipe Cost	$	Cost of trunk pipe	NA	Calculated in Equation 19
Trunk Pipe Unit Cost	$/ft	Unit cost of trunk pipe	$ 15/ft	*AMDTreat® v.4.1*

[a]Effluent Scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent Scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.1.5   *Total Capital Costs*

The total capital cost of the limestone bed includes the cost of the limestone, soil excavation, liner, piping, and installation.

Equation 26 calculates the total capital cost of the limestone bed with a clay liner.

$$\text{Total Capital Cost}_{Clay} = \text{Limestone Cost} + \text{Excavation Cost} + \text{Clay Liner Cost} + \text{Piping Cost} \qquad (26)$$

Equation 27 calculates the total capital cost of the limestone bed with a synthetic liner.

$$\text{Total Capital Cost}_{Synthetic} = \text{Limestone Cost} + \text{Excavation Cost} + \text{Synthetic Liner Cost} + \text{Piping Cost} \qquad (27)$$

Table 4-5 describes the variables in the total capital cost section of the limestone bed cost module shown in Equations 25 and 26 and provides the values used in the equations for each effluent scenario.

Table 4-5. Total Capital Cost Variable Description

Variable	Units	Variable Description	Effluent Scenarios 1[a] and 2[b]	
			Value	Value Source
Clay Liner Cost	$	Cost of clay liner	NA	Calculated in Equation 17
Excavation Cost	$	Cost of excavating soil for the limestone bed	NA	Calculated in Equation 10

Table 4-5. Total Capital Cost Variable Description

Variable	Units	Variable Description	Effluent Scenarios 1[a] and 2[b]	
			Value	Value Source
Limestone Cost	$	Cost of limestone required to achieve desired pH	NA	Calculated in Equation 3
Piping Cost	$	Total cost of piping	NA	Calculated in Equation 25
Synthetic Liner Cost	$	Cost of synthetic liner	NA	Calculated in Equation 18
Total Capital Cost$_{Clay}$	$	Total capital cost of the limestone bed using a clay liner	NA	Calculated in Equation 26
Total Capital Cost$_{Synthetic}$	$	Total capital cost of the limestone bed using a synthetic liner	NA	Calculated in Equation 27

[a]Effluent Scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR Part 434.
[b]Effluent Scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2   Annual Costs

The annual costs for a limestone bed treatment system include the following items:

- Sludge removal cost;
- Limestone turning cost;
- Sampling cost; and
- Maintenance labor cost.

The following sections describe how each of these costs is calculated in the limestone bed module. The sampling cost and maintenance costs will be the same for both effluent scenario because these portions of the cost module do not depend on effluent water characteristics. Therefore, the sampling cost and maintenance cost for each effluent scenario will off-set when the total costs are compared. However, these costs are included for comparison to other costing modules in EPA's Detailed Study of the Coal Mining Point Source Category.

4.2.1   Sludge Removal Cost

The sludge generated annually depends on the water chemistry, such as final pH and ion concentrations, and settling pond retention time. EPA assumes that when the discharge reaches pH 10 for effluent scenario 1, the following effluent quality will be achieved based on metal solubilities from Figure 2-2 (Means, 2004)[5]:

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[5] EPA received comments from Dr. Charles Cravotta (U.S.G.S.) and Mr. Brent Means (OSMRE), regarding EPA's assumption that Part 434 limits would be achieved if pH is adjusted to a certain point (i.e., that the iron monthly average limit of 3.0 mg/L would be achieved if pH is adjusted to 8.3, and that the manganese monthly average limit of 2 mg/L would be achieved if pH is adjusted to 10). Both scientists point out the limitations of such assumptions. Dr. Cravotta has demonstrated that effluent pH may be a poor means of quantifying the effluent quality. That is, in

- Iron at 3.0 mg/L;
- Manganese at 2.0 mg/L;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

EPA assumes that when the discharges reaches pH 7 for effluent scenario 2, the following effluent quality will be achieved based on metals solubilities from Figure 2-2 (Means, 2004):[6]

- Iron at 3.0 mg/L;
- A 10 percent reduction in manganese from untreated;
- A 99 percent reduction in aluminum from untreated; and
- A 10 percent reduction in magnesium from untreated.

This cost module does not include the amount of sludge generated from other insoluble metal hydroxides; however, it over estimates sludge resulting from the iron, aluminum, manganese, and magnesium.

Equations 27 through 30 calculate the amount of sludge generated from aluminum, iron, manganese, and magnesium, respectively. Equation 31 calculates the annual sludge removal cost.

$$Sludge_{Al} = Al * Al_{reduction} * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \, Solids} \tag{27}$$

$$Sludge_{Fe} = \{(Fe^{3+} + Fe^{2+}) - Fe_{limit}\} * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \, Solids} \tag{28}$$

$$Sludge_{Mn} = \{(Mn - Mn_{limit}) * Mn_{reduction} * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \, Solids} \tag{29}$$

$$Sludge_{Mg} = Mg * Mg_{reduction} * Flow * \frac{CF_{volume}}{CF_{weight}} * CF_{time} * \frac{1}{Density_{sludge}} * \frac{1}{\% \, Solids} \tag{30}$$

$$Annual \, Sludge \, Cost = \{Sludge_{Al} + Sludge_{Fe} + Sludge_{Mn} + Sludge_{Mg}\} * Removal \, Cost \tag{31}$$

Table 4-6 describes the variables in the sludge removal cost section of the limestone bed cost module shown in Equations 27 through 31 and provides the values used in the equations for each effluent scenario.

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some cases, especially when ferrous iron is present in the AMD, an effluent pH of 8.3 may still result in effluent iron levels that consistently exceed the 3.0 mg/L monthly limit. EPA is considering refining future treatment cost estimates with continued input from Dr. Cravotta and Mr. Means, and EPA recognizes that the cost estimates resulting from these modules represent gross cost estimates. For this stage of EPA's evaluation of the Detailed Study of the Coal Mining Industry, these gross cost estimates sufficiently address EPA's question of how much extra cost the industry incurs to treat AMD for manganese, rather than solely for iron. The costs estimated for sludge removal represent between 0.5 percent and 6.5 percent of the total annualized cost.
[6] Ibid.

Table 4-6. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
% Solids	%	Ratio of the weight of solids to the weight of water	5 %	*AMDTreat® v.4.1*	5 %	*AMDTreat® v.4.1*
Al	mg/L	Aluminum concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
$Al_{reduction}$	%	Percent reduction of aluminum from untreated to final effluent	99 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	99 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 31	NA	Calculated in Equation 31
CF_{time}	min/yr	Conversion factor for converting minutes to years	525,600 min/yr	Constant	525,600 min/yr	Constant
CF_{volume}	L/gal	Conversion factor for converting liters to gallons	3.785 L/gal	Constant	3.785 L/gal	Constant
CF_{weight}	mg/lb	Conversion factor for converting milligrams to pounds	454,000 mg/lb	Constant	454,000 mg/lb	Constant
$Density_{sludge}$	lb/gal	Density of solids and water in sludge	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density	8.33 lb/gal	*AMDTreat® v.4.1* - Assumes same as water density
Fe^{2+}	mg/L	Ferrous iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe^{3+}	mg/L	Ferric iron concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Fe_{limit}	mg/L	Effluent limit for iron	3.0 mg/L	40 CFR Part 434	3.0 mg/L	40 CFR Part 434
Flow	gpm	Discharge flow	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mg	mg/L	Magnesium concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics

Table 4-6. Sludge Removal Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a]		Effluent Scenario 2[b]	
			Value	Value Source	Value	Value Source
Mg_reduction	mg/L	Percent reduction of magnesium from untreated to final effluent	10 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)	0 %	*Comparison of Three Methods to Measure Acidity of Coal-Mine Drainage* (Means, 2004)
Mn	mg/L	Manganese concentration in untreated discharge	Input Parameter	Model Mine Characteristics	Input Parameter	Model Mine Characteristics
Mn_limit	mg/L	Effluent limit for manganese	2.0 mg/L	40 CFR Part 434	0	Effluent value will be estimated based on performance data received from coal mines with chemical precipitation
Removal Cost	$/gal	Cost of removing sludge	$ 0.06/gal	*AMDTreat® v.4.1*	$ 0.06/gal	*AMDTreat® v.4.1*
Sludge_Al	gal/yr	Amount of sludge generated from the precipitation of aluminum	NA	Calculated in Equation 27	NA	Calculated in Equation 27
Sludge_Fe	gal/yr	Amount of sludge generated from the precipitation of iron	NA	Calculated in Equation 28	NA	Calculated in Equation 28
Sludge_Mg	gal/yr	Amount of sludge generated from the precipitation of magnesium	NA	Calculated in Equation 30	NA	Calculated in Equation 30
Sludge_Mn	gal/yr	Amount of sludge generated from the precipitation of manganese	NA	Calculated in Equation 29	NA	Calculated in Equation 29

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2.2 Limestone Turning Cost

The limestone turning cost includes the labor required to turn the limestone in the limestone bed to flush out the insoluble metal hydroxides that settle in the limestone bed and armor the limestone. The insoluble metal hydroxides coat the limestone and reduce the ability of the limestone to react with the discharge. This cost module assumes that the limestone in the limestone bed needs turned every two years to remove the insoluble metal hydroxides (ERG, 2006). This cost module also assumes that the cost of excavating the limestone every two years is equal to the excavation cost from Equation 10.

Equation 32 calculates the annual limestone turning cost assuming every time the limestone requires turning the cost is equal to the excavation cost from Equation 10, which occurs every five years.

$$\text{Limestone Turing Cost} = \frac{\text{Excavation Cost}}{\text{Turing Time}} \tag{32}$$

Table 4-7 describes the variables in the sampling cost section of the limestone bed cost module shown in Equation 32 and provides the values used in equations for both effluent scenarios. The sampling costs are the same for both effluent scenarios.

Table 4-7. Limestone Turning Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Excavation Cost	$	Cost of excavating soil for the limestone bed	NA	Calculated in Equation 10
Limestone Turning Cost	$/yr	Cost of turning the limestone to remove the insoluble metal hydroxides that settled in the limestone bed	NA	Calculated in Equation 32
Turning Time	yr	Frequency of turning the limestone in the limestone bed	2 yr	"Site Visit Report Pennsylvania Coal Mine Acid Drainage Treatment Systems" (ERG, 2006)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2.3 Sampling Cost

The annual sampling cost includes the labor for collecting the samples and the sampling lab analysis costs. This cost module assumes that the number of samples required yearly is independent of the flow, net acidity, raw AMD metals concentrations, or treatment technology. Based on conversations with coal mine wastewater treatment operators, sampling is only conducted to meet the NPDES permit requirements (Wolford, 2007b; Wolford, 2007c). The

sampling costs for both effluent scenarios are the same because sampling requirements are independent of effluent quality. EPA included the sampling cost anyway.

Equations 33 through 36 calculate the annual sampling cost assuming the NPDES permits require bi-monthly sampling.

$$\text{Collection Labor} = \text{Sampling Points} * \text{Collection Time} * \text{Monthly Frequency} * CF_{time} * \text{Labor Cost} \quad (33)$$

$$\text{Travel Labor} = \text{Monthly Frequency} * \text{Travel Time} * CF_{time} * \text{Labor Cost} \quad (34)$$

$$\text{Lab Cost} = \text{Sampling Points} * \text{Monthly Frequency} * CF_{time} * \text{Sample Cost} \quad (35)$$

$$\text{Annual Sampling Cost} = \text{Collection Labor} + \text{Travel Labor} + \text{Lab Cost} \quad (36)$$

Table 4-8 describes the variables in the sampling cost section of the limestone bed cost module shown in Equations 33 through 36 and provides the values used in equations for both effluent scenarios. The sampling costs are the same for both effluent scenarios.

Table 4-8. Sampling Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 36
CF_{time}	mo/yr	Conversion factor for converting months to years	12 mo/yr	Constant
Collection Labor	$/yr	Annual labor cost for worker to collect samples	NA	Calculated in Equation 33
Collection Time	hr	Average time expected for the worker to collect one sample	0.33 hr	*AMDTreat® v.4.1*
Lab Cost	$/yr	Annual cost for laboratory analysis	NA	Calculated in Equation 35
Labor Rate	$/hr	Hourly rate for worker	$ 35.00/hr	*AMDTreat® v.4.1*
Monthly Frequency	No./month	Number of samples collected per month	2/month	*AMDTreat® v.4.1*
Sample Cost	$/sample	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	*AMDTreat® v.4.1*
Sampling Points	No.	Number of sampling points in treatment system	3	*AMDTreat® v.4.1*- Assumes sampling effluent and upstream and downstream of the discharge location
Travel Labor	$/yr	Annual labor cost for worker to travel to site	NA	Calculated in Equation 34
Travel Time	hr	Time expected for worker to travel from the office to the site	1 hr	*AMDTreat® v.4.1*

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2.4 Maintenance Labor Cost

The labor cost associated with maintaining the limestone bed treatment system is based on the weekly site visits required by the operator to make sure the system is operating correctly. Mr. Mark Tercek of PBS Coals, Inc. reported that passive treatment systems, including limestone beds, require operators to check the site weekly or bi-weekly (Wolford, 2007c). EPA assumed that passive treatment systems require operators to check the site weekly. The maintenance labor cost does not depend on effluent water characteristics but rather the type of treatment system; therefore, the maintenance labor cost is the same for both effluent scenarios. The maintenance labor cost does not include the annual cost of replacing mechanical parts because EPA assumes the cost would be the same for both effluent scenarios.

Equation 37 calculates the cost of labor required to maintain the limestone bed.

Annual Maintenance Cost = Visits per Week * {Labor Time + Travel Time} * Labor Rate * CF_{time} (37)

Table 4-9 describes the variables in the maintenance labor cost section of the hydrated lime cost module shown in Equation 37 and provides the values used in equations for both effluent scenarios. The maintenance labor cost variables are the same for both effluent scenarios.

Table 4-9. Maintenance Labor Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 37
CF_{time}	wk/yr	Conversion factor for converting weeks to years	52 wk/yr	Constant
Labor Rate	$/hr	Hourly rate for worker	$ 35.00/hr	*AMDTreat® v.4.1*
Labor Time	hr	Time expected for worker to inspect the treatment system and ensure it's working correctly	2 hr	*AMDTreat® v.4.1*
Travel Time	hr	Time expected for worker to travel from the office to the site	1 hr	*AMDTreat® v.4.1*
Visits per Week	No./wk	Number of visits required to maintain the system per week	1/wk	Personal communication with Mr. Mark Tercek, PBS Coals, Inc. (Wolford, 2007c)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.2.5   Total Annual Cost

Equation 38 calculates the total annual costs for the limestone bed system.

Total Annual Cost = Annual Sludge Cost + Annual Sampling Cost + Annual Maintenance   (38)

Table 4-10 describes the variables in the total annual cost section of the limestone bed module shown in Equation 38 and provides the values used in the equations for both effluent scenarios. The total annual cost variables are the same for both effluent scenarios.

Table 4-10. Total Annual Cost Variable Descriptions

Variable	Variable Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annual Maintenance Cost	$/yr	Annual maintenance cost	NA	Calculated in Equation 37
Annual Sampling Cost	$/yr	Annual sampling cost	NA	Calculated in Equation 36
Annual Sludge Cost	$/yr	Annual cost of removing sludge	NA	Calculated in Equation 31
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 38

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

4.3   **Effluent Scenario Cost Comparison**

EPA is estimating the cost difference between using chemical precipitation and other treatment technologies to achieve two different effluent scenarios:

1. To meet all of the 40 CFR Part 434 limits (TSS, pH, iron, and manganese); and
2. To meet only the TSS, pH, and iron limits in 40 CFR Part 434.

Prior to calculating the cost difference, the capital costs must be annualized for each effluent scenario. Equations 39 and 40 calculate the total annualized costs for the hydrated lime chemical precipitation system.

$$\text{Annualized Capital Cost} = \text{Total Capital Cost} * \frac{\text{Interest} * (1 + \text{Interest})^{\text{years}}}{(1 + \text{Interest})^{\text{years}} - 1} \qquad (39)$$

Total Annualized Cost = Annualized Capital Cost + Total Annual Cost   (40)

Equation 41 compares the total annualized cost for effluent scenario 1 with the total annualized cost for effluent scenario 2.

Net Annual Cost = Total Annualized Cost$_{\text{Effluent Scenario 1}}$ − Total Annualized Cost$_{\text{Effluent Scenario 2}}$ (41)

Table 4-11 describes the variables in the effluent scenario cost comparison section of the hydrated lime cost module shown in equations 39, 40, and 41 and provides the values used in the equations for each effluent scenario.

Table 4-11. Effluent Scenario Cost Comparison Variable Descriptions

Variable	Units	Variable Description	Effluent Scenario 1[a] and 2[b]	
			Value	Value Source
Annualized Capital Cost	$/yr	Annualized capital cost for hydrated lime treatment system	NA	Calculated in Equation 39
Interest	%	Interest rate for annualization	10 %	EPA
Net Annual Cost	$/yr	Net annual cost to increase from pH 8.3 to pH 10 using hydrated lime treatment system	NA	Calculated in Equation 41
Total Annual Cost	$/yr	Total annual cost	NA	Calculated in Equation 38
Total Annualized Cost	$/yr	Total annualized cost (capital and annual) for caustic treatment system	NA	Calculated in Equation 40
Total Capital Cost	$	Total capital cost for the hydrated lime treatment system	NA	Calculated in Equation 27
Years	yr	Years for annualization calculation	75 yr	*PA DEP Bureau of Mining and Reclamation Technical Guidance Document: Evaluating Postmining Discharges* (PA DEP, 1997)

[a]Effluent scenario 1 estimates the cost of treating AMD to meet the limits in 40 CFR part 434.
[b]Effluent scenario 2 estimates the cost of treating AMD to meet only the TSS, pH, and iron limits in 40 CFR Part 434.

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Attachment A – *AMDTreat*® *v.4.1* **Default Values for Limestone Bed Cost Module**

Table A-1. *AMDTreat® v.4.1* **Default Values for the Limestone Bed Cost Module**

Variable	Variable Description	*AMDTreat® v.4.1* Default Value	Equation Reference
% Solids	Ratio of the weight of solids to the weight of water	5 %	27, 28, 29, 30
Clay Liner Unit Cost	Unit cost of clay liner	$ 5/yd^3	17
Collection Time	Average time expected for the worker to collect one sample	0.33 hr	33
Density	Density of loose limestone in the limestone bed as delivered to the site including void space	94.3 lb/ft^3	3, 4
Density$_{Sludge}$	Density of solids and water in sludge	8.33 lb/gal	27, 28, 29, 30
Depth$_{FB}$	Depth of freeboard in the limestone bed	3 ft	13, 14, 16
Depth$_{LS}$	Depth of limestone in limestone bed	3 ft	5, 11, 12, 16
Depth$_{Water}$	Depth of water layer in the limestone bed	2 ft	7, 8, 9, 16
E/I Pipe	Length of effluent and influent pipe to the limestone bed	20 ft	19, 20, 23, 24
Efficiency	Efficiency of limestone at imparting alkalinity	60 %	2
Excavation Unit Cost	Cost of excavating	$ 5.5/yd^3	10
Install Rate	Pipe installation rate	11 ft/hr	23, 24
Labor Rate	Cost of labor	$ 35/hr	23, 24, 37
Labor Time	Time expected for worker to inspect the treatment system and ensure it's working correctly	2 hr	37
Length$_{Spur}$	Length of spur pipe segment	20 ft	21, 22, 23, 24
Length$_{Trunk}$	Length of a trunk pipe segment	20 ft/segment	19, 20, 23, 24
Limestone Placement Cost	Cost of placing the limestone into the limestone bed	$ 2/yd^3	3
Limestone Unit Cost	Cost of limestone	$ 22/ton	3
Monthly Frequency	Number of samples collected per month	2/month	33, 34, 35
Purity	Purity of limestone	85 %	2
Removal Cost	Cost of removing sludge	$ 0.06/gal	31
Sample Cost	Cost of laboratory analysis for one sample for all analytical tests	$ 27.00/sample	34
Sampling Points	Number of sampling points in treatment system	3	33
Slope	Slope of the sides of the limestone bed	0.5	5, 7, 8, 9, 11, 12, 13, 14, 15
Spur Coupler Unit Cost	Unit cost of coupler for the spur pipe segments	$ 3/coupler	22
Spur Spacing	Spacing between spur segments	10 ft	21, 22, 23, 24
Spur Unit Cost	Unit cost of spur pipe	$ 7/ft	21
Synthetic Liner Unit Cost	Unit cost of synthetic liner	$ 5.50/yd^2	18
Thickness	Clay liner thickness	0.5 ft	17

Table A-1. *AMDTreat® v.4.1* **Default Values for the Limestone Bed Cost Module**

Variable	Variable Description	*AMDTreat® v.4.1* Default Value	Equation Reference
Travel Time	Time expected for worker to travel from the office to the site	1 hr	34, 37
Trunk Coupler Unit Cost	Unit cost of coupler for the trunk pipe segments	$ 6.6/coupler	20
Trunk Pipe Unit Cost	Unit cost of trunk pipe	$ 15/ft	19

Source: *AMDTreat® v.4.1*.

Appendix E

ACID MINE DRAINAGE TREATMENT COST MODULE RESULTS

Table E-1. Cost Summary: Chemical Precipitation Using Caustic Soda
Table E-2. Cost Summary: Chemical Precipitation Using Hydrated Lime
Table E-3. Cost Summary: Limestone Bed with Clay Liner
Table E-4. Cost Summary: Limestone Bed with Synthetic Liner

Table E-1. Cost Summary: Chemical Precipitation Using Caustic Soda

Flow (gpm)	Net Delta Capital Cost ($)	Net Delta Annual Cost ($/yr)	Net Delta Annualized Cost to Treat to Manganese Limit ($/yr)
Net Alkaline, Low Metals			
10	0	6,331	6,331
250	16,000	158,927	160,528
500	30,000	317,774	320,776
1,000	60,000	635,548	641,552
1,500	90,000	953,322	962,329
Net Alkaline, High Metals			
10	4,000	36,120	36,520
250	86,000	902,431	911,038
500	170,000	1,804,782	1,821,795
1,000	340,000	3,609,563	3,643,590
1,500	510,000	5,414,345	5,465,385
Net Acidic, Low Metals			
10	0	7,083	7,083
250	18,000	177,789	179,590
500	34,000	355,498	358,901
1,000	66,000	710,916	717,521
1,500	102,000	1,066,494	1,076,702
Net Acidic, High Metals			
10	4,000	36,871	37,271
250	86,000	921,213	929,820
500	174,000	1,842,506	1,859,920
1,000	348,000	3,685,012	3,719,839
1,500	522,000	5,527,518	5,579,759

Table E-2. Cost Summary: Chemical Precipitation Using Hydrated Lime

Flow (gpm)	Net Delta Capital Cost ($)	Net Delta Annual Cost ($/yr)	Net Delta Annualized Cost to Treat to Manganese Limit ($/yr)
Net Alkaline, Low Metals			
10	0	720	720
250	0	19,668	19,668
500	0	37,682	37,682
1,000	2,000	73,784	73,984
1,500	7,000	110,000	110,701
Net Alkaline, High Metals			
10	0	4,517	4,517
250	7,000	113,216	113,916
500	37,000	227,352	231,055
1,000	70,000	454,544	461,549
1,500	130,000	682,816	695,826
Net Acidic, Low Metals			
10	0	783	783
250	0	19,566	19,566
500	0	39,132	39,132
1,000	2,000	78,344	78,544
1,500	7,000	117,676	118,377
Net Acidic, High Metals			
10	0	4,580	4,580
250	7,000	114,786	115,486
500	35,000	230,411	233,914
1,000	70,000	460,823	467,828
1,500	105,000	691,234	701,742

Table E-3. Cost Summary: Limestone Bed with Clay Liner

Flow (gpm)	Net Delta Capital Cost ($)	Net Delta Annual Cost ($/yr)	Net Delta Annualized Cost to Treat to Manganese Limit ($/yr)
Net Alkaline, Low Metals			
10	17,558	1,613	3,370
250	400,333	37,469	77,534
500	791,165	74,522	153,701
1,000	1,572,230	148,457	305,803
1,500	2,359,613	222,294	458,441
Net Alkaline, High Metals			
10	91,350	8,747	17,889
250	2,225,898	212,271	435,036
500	4,456,193	423,605	869,575
1,000	8,885,635	845,885	1,735,148
1,500	13,287,754	1,267,947	2,597,768
Net Acidic, Low Metals			
10	18,395	1,784	3,625
250	447,655	41,774	86,575
500	879,742	83,136	171,179
1,000	1,755,110	165,688	341,337
1,500	2,631,961	248,145	511,548
Net Acidic, High Metals			
10	91,778	8,919	18,104
250	2,268,900	216,582	443,651
500	4,524,014	432,227	884,984
1,000	9,042,029	863,129	1,768,043
1,500	13,566,643	1,293,812	2,651,544

Table E-4. Cost Summary: Limestone Bed with Synthetic Liner

Flow (gpm)	Net Delta Capital Cost ($)	Net Delta Annual Cost ($/yr)	Net Delta Annualized Cost to Treat to Manganese Limit ($/yr)
Net Alkaline, Low Metals			
10	20,111	1,613	3,625
250	442,581	37,469	81,762
500	872,508	74,522	161,842
1,000	1,730,455	148,457	321,638
1,500	2,593,988	222,294	481,897
Net Alkaline, High Metals			
10	102,129	8,747	18,968
250	2,446,825	212,271	457,146
500	4,890,942	423,605	913,084
1,000	9,745,084	845,885	1,821,160
1,500	14,570,249	1,267,947	2,726,118
Net Acidic, Low Metals			
10	21,113	1,784	3,897
250	494,243	41,774	91,237
500	969,795	83,136	180,191
1,000	1,930,796	165,688	358,920
1,500	2,892,554	248,145	537,628
Net Acidic, High Metals			
10	102,731	8,919	19,201
250	2,494,212	216,582	466,199
500	4,967,535	432,227	929,371
1,000	9,919,027	863,129	1,855,812
1,500	14,875,465	1,293,812	2,782,529