ABSTRACT

In the past, Illinois Environmental Protection Agency (IEPA) has regulated mine discharges under the Pollution Control Board's Subtitle D regulations and has required these discharges to comply with sulfate effluent limitation of 3,500 mg/L. More recently, both U.S. Environmental Protection Agency (USEPA) and IEPA have been regulating these discharges under the Subtitle C general use water quality standard of 500 mg/L. Mine operators are seeking alternatives that would help to comply with the general use water quality standard for sulfate. Since compliance with the general use standard may negatively impact competitiveness of Illinois coal industry, coal professionals and environmental groups are working with IEPA and USEPA to develop a sulfate standard that will be technically sound and environmentally protective. Also, IEPA has allowed mine discharges to comply with chloride effluent limitation of 1,000 mg/L in the past. However, IEPA now requires discharges to comply with Subtitle C general use water quality standard of 500 mg/L.

To assist the coal industry with meeting the evolving standards, this study was aimed to identify good management practices (GMPs) for minimizing sulfate and chloride discharges from Illinois coal mines. The goals were to 1) survey current management practices for controlling sulfate and chloride discharges from mining operations at NPDES locations, 2) assess effectiveness of the identified practices, and 3) develop an inventory of good practices for use and consideration by the coal industry at their specific sites. Study was based on literature review, interviews with professional experts, visits to mining and processing operations, limited laboratory studies and analysis of historical water quality data and water quality data collected during visits to active mining sites. Identified GMPs were divided into two categories: proven good management practices (PGMPs) and conceptual good management practices (CGMPs). The PGMPs’ effectiveness in minimizing sulfate discharges has been field demonstrated in the past. The CGMPs present concepts that are founded on scientific principles that have potential to minimize sulfate discharges but need further development and field demonstration. The study suggests that additional dilution is the only practical approach to comply with reduced chloride standard.
Illinois mining operations discharge sulfate in water at the National Pollutant Discharge Elimination System (NPDES) designated discharge points. It is well recognized that sulfates are primarily generated through oxidation and leaching of pyrite in selected overburden rocks and coal processing waste. As a result of this weathering process, sulfates will be generated regardless of management practices in place. Mining operation permits recognize that some amount of sulfates will be discharged by the mining, processing, and waste management. The permit approval is based on demonstrating that the discharges of sulfate and chloride will be minimized and will meet allowable limits. In the past, IEPA has regulated mine discharges under the Pollution Control Board's Subtitle D regulations and has required these discharges to comply with sulfate effluent limitation of 3,500 mg/L. More recently, both USEPA and IEPA has been regulating these discharges under the Subtitle C general use water quality standard of 500 mg/L. Mine operators are therefore looking into alternatives that would help them to comply with the general use water quality standard for sulfate. Since compliance to the general use standard may negatively impact competitiveness of Illinois coal industry, coal professionals and environmental groups are working with IEPA and USEPA to develop a sulfate standard that will be technically sound and environmentally protective. Also, IEPA has allowed mine discharges to comply with chloride effluent limitation of 1,000 mg/L in the past. However, IEPA now requires mine discharges to comply with the Subtitle C general use water quality standard of 500 mg/L.

The Advent Group, Inc (2005) performed a study to evaluate the cost impact of reducing the current 3,500 mg/L sulfate effluent limitation for Illinois mines to 500 mg/L general use standard. The data for analysis was collected from IEPA, and some of the data is from non-active but permitted sites.

- Eighty eight NPDES permits were reviewed that included 268 outfalls.
- Of these 16% had sulfate concentrations greater than 2,500 mg/L, while 37% had sulfate concentration in the 500 to 2,000 mg/L range.
- The average sulfate concentration for all outfalls was 621 mg/L.
- Compliance to 500 mg/L sulfate standard will have a major economic impact on Illinois coal mines by significantly increasing the cost for operating coal mines. They assessed the difference in cost impact to the industry if the sulfate standard was increased from 500 mg/L to 2,000 mg/L. For this analysis, two technologies were considered: 1) addition of an excessive amount of hydrated lime for precipitation of sulfate down to 2,000 mg/L followed by addition of hydrochloric acid for pH adjustment, and 2) application of caustic/nano-filtration system for compliance with 500 mg/L standard.
- Over a ten-year period, the cost to comply with 500 mg/L standard will be 7.5 billion dollars for affected Illinois coal mines. Over the same period, the cost to comply with 2,000 mg/L standard will be 730 million dollars.
- An analysis of sulfate concentration in surface monitoring stations in Illinois indicated: 1) about 2.8% of the points had an average concentration above 500
mg/L, while 12.4% had maximum sulfate concentrations above 500 mg/L, and 2) about 7.3% of the points had maximum sulfate concentration about 2,000 mg/L.

A similar analysis of 3,080 individual chloride concentrations data (Crislip, 2005) indicated the following.

- About 4.7% of samples exceeded 1,000 mg/L, while an additional 1.8% of the samples ranged 750–1,000 mg/L.
- Of the 73 facilities, where the above samples were collected, 9 facilities exceeded 1,000 mg/L and 13 facilities had chloride concentrations in the range 750–1,000 mg/L.

The observations above suggested that before implementing any treatment approach to reduce sulfate concentrations, attempts should be made to minimize sulfate discharges through implementation of good operations management practices that are significantly lower cost and would have minimal side effects of using chemical treatment practices. Therefore, this study was initiated to identify and assess good management practices (GMPs) for minimizing sulfate and chloride discharges from coal mines. Their implementation should reduce water treatment cost (that can be technically challenging and cost prohibitive) and minimize the negative impacts of implementing any new sulfate standards less than 3,500 mg/L. The goals of this study were to 1) survey coal processing waste (coal refuse) management practices for controlling sulfate and chloride discharges from mining operations at NPDES locations, 2) assess effectiveness of the identified practices, and 3) develop an inventory of GMPs that can be considered by operators on a site specific basis to develop best management practices (BMPs).

The overall study was performed through 1) pertinent literature review, 2) questionnaire and personal interview data collection and data analysis from selected organizations and professionals throughout USA, with emphasis on adjoining high sulfur coal mining states, 3) survey of selected mining, processing and waste management operations in Illinois for review of management practices for sulfate and chloride control, 4) analysis of historical water quality data and water quality data collected during visits to surveyed mine sites to correlate management practices and water quality, 5) identification of management practices that pointed toward lower discharge of sulfates and chlorides, 6) identification of good management practices with high commercial potential based on professional judgment and input from peers, and 7) development of recommendations for good management practices in the area of pre-mining characterization, permitting process requirements, mining and reclamation operations, and monitoring and control requirements.

The GMPs were divided into two categories: proven good management practices (PGMPs) and conceptual good management practices (CGMPs). PGMPs are proven practices and their use and effectiveness is well documented in Illinois or elsewhere. Examples of such practices include 1) minimize period of weathering and oxidation
of overburden and coal processing waste to less than 12 months based on their geochemistry and local temperature and precipitation environment, 2) contemporaneous reclamation to the extent possible to minimize large areas susceptible to oxidation and acidification, 3) appropriate compaction of coarse waste, 4) minimizing the formation of deltas of pyrite-rich slurry fines exposed above the water table and capillary zone through the application of movable, low scouring slurry discharge points. The project team believes that careful implementation of PGMPs can assist mine operators in Illinois to improve upon current high sulfate discharge concentrations in some mines. CGMPs on the other hand are founded on sound scientific principles but require additional development and field demonstration. The project team believes that CGMPs should be further developed through additional research and development. These have the potential to significantly minimize long-term liability of mine operators for water treatment and environmental damage. The project team also believes that permit application should include 1) additional geochemical characterization of coal seam and immediate roof and floor strata during pre-mining phase to assess potential for excessive sulfate and chloride discharge, 2) utilize the above data to plan waste and water management operations to achieve desired discharges to the extent possible, 3) discussion of how the mine operator plans to utilize GMPs to minimize sulfate and chloride discharges, 4) additional geochemical characterization of different fractions of coal processing waste (as it comes out of the processing plant) to support or modify planning of waste management operations from pre-mining phase, 5) discussion of the steps that the operator plans to take to minimize sulfate and chloride discharges, and 6) periodic discharge of water and use of mixing zones where chloride concentrations are expected to be high.

** The term “coal refuse” refers to coal processing waste and reject from rotary breakers prior to the run-of-mine (ROM) coal entering the processing plant. Coal refuse consists of typically two fractions: 1) coarse coal processing waste (CCPW), generally larger than 100 mesh (150 micron) size or in some cases larger than 1/8 inch size, and 2) fine coal processing waste (FCPW) or slurry generally less than 100 mesh sizes. These terms are used throughout this report and sometimes interchangeably.
DISCLAIMER STATEMENT

This report was prepared by Prof. Y.P. Chugh, Southern Illinois University Carbondale, with support, in part, by grants made possible by the Illinois Department of Commerce and Economic Opportunity through the Office of Coal Development and the Illinois Clean Coal Institute. Neither Prof. Y.P. Chugh, Southern Illinois University Carbondale, nor any of its subcontractors, nor the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development, the Illinois Clean Coal Institute, nor any person acting on behalf of either:

(A) Makes any warranty of representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring; nor do the views and opinions of authors expressed herein necessarily state or reflect those of the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development, or the Illinois Clean Coal Institute.

Notice to Journalists and Publishers: If you borrow information from any part of this report, you must include a statement about the state of Illinois' support of the project.
IDENTIFICATION AND ASSESSMENT OF BEST MANAGEMENT PRACTICES IN ILLINOIS MINING OPERATIONS TO MINIMIZE SULFATE AND CHLORIDE DISCHARGES

Final Report

Yoginder P. Chugh
Samrat Mohanty
Paul Behum
Jack Nawrot
William Bell

1Mining and Mineral Resources Engineering
2Cooperative Wildlife Research Laboratory
Southern Illinois University
Carbondale, Illinois 62901

For
Illinois Clean Coal Institute

June 2007
LIST OF TABLES
LIST OF FIGURES
ACKNOWLEDGEMENTS
ABSTRACT
EXECUTIVE SUMMARY

CHAPTER 1: INTRODUCTION AND BACKGROUND
1.1 Background
1.2 Problem Statement
1.3 Significance of Study
1.4 Scope of Study
1.5 Experimental and Study Procedures
1.6 Report Organization

CHAPTER 2: REVIEW OF PERTINENT LITERATURE: SULFATE DISCHARGES
2.1 Introduction
2.2 Sulfate Discharge in Coal Mines
2.3 Geochemistry of AMD Production
2.4 Common Sulfate Sources
2.5 Characteristics of Illinois Coal
2.6 Other Geochemical Factors Associated with Sulfate Generation
2.7 Gaps in Current Knowledge Base

CHAPTER 3: REVIEW OF PERTINENT LITERATURE: CHLORIDE DISCHARGES
3.1 Introduction
3.2 Chlorine in Illinois Coals
3.3 Gaps in Current Knowledge Base

CHAPTER 4: PERMIT APPLICATION DOCUMENTS
4.1 Introduction
4.2 Task Approach
4.3 Variables Studied
4.4 Geo-mining Factors
4.5 Hydro-geologic Factors
4.6 Refuse Characteristics
4.7 Hydro-geologic Impact Statement
4.8 Current Waste Management Practices in Underground Coal Mines
4.9 Current Spoil Management Practices in Surface Coal Mines
4.10 Operational Factors
4.11 Reclamation Factors
4.12 Inter-relationships between Factors
4.13 Good Management Practices
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Median and range of minerals in Illinois coal</td>
<td>12</td>
</tr>
<tr>
<td>3.1</td>
<td>Total and Water-soluble Chlorine of Illinois Coal</td>
<td>22</td>
</tr>
<tr>
<td>5.1</td>
<td>Preliminary intra-plant water sampling in selected Illinois coal mines</td>
<td>47</td>
</tr>
<tr>
<td>6.1</td>
<td>Summarized geochemical properties of Illinois coal refuse (Limited sampling)</td>
<td>59</td>
</tr>
<tr>
<td>6.2</td>
<td>Current CCPW management practices</td>
<td>62</td>
</tr>
<tr>
<td>6.3</td>
<td>Current FCPW management practices</td>
<td>62</td>
</tr>
<tr>
<td>6.4</td>
<td>Water management practices</td>
<td>63</td>
</tr>
<tr>
<td>6.5</td>
<td>Summarized geochemical properties of Illinois coal refuse</td>
<td>59</td>
</tr>
<tr>
<td>7.1</td>
<td>Typical geochemical profile of oxidized surface (0-6”) and un-oxidized saturated slurry (30-36”) samples (annual monitoring average values) from an Illinois Coal Basin 170–acre slurry cell direct seeded using ILAP (from: Nawrot 2004)</td>
<td>71</td>
</tr>
<tr>
<td>7.2</td>
<td>Hypothetical mixing application: dilution by receiving stream with mixing zone only</td>
<td>77</td>
</tr>
<tr>
<td>7.3</td>
<td>Hypothetical mixing zone application: dilution by receiving stream mixing and aided by an on-site fresh water source</td>
<td>78</td>
</tr>
<tr>
<td>8.1</td>
<td>Physio-chemical properties associated with differential distribution of slurry components based on distance from the discharge point</td>
<td>82</td>
</tr>
<tr>
<td>8.2</td>
<td>Acid balance resulting from segregated disposal in southern Illinois</td>
<td>82</td>
</tr>
<tr>
<td>8.3</td>
<td>Results of pilots scale testing of coal slurry by Parekh et al. (2005)</td>
<td>95</td>
</tr>
<tr>
<td>9.1</td>
<td>Results of field compaction assessment</td>
<td>105</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1: Proposed flow chart for the study 4
Figure 2.1: Sulfate occurrences in U.S. coals (Gluskoter and others, 1977) 10
Figure 2.2: Total sulfur content (wt, %) in the Springfield No. 5 coal (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_totals.pdf) 14
Figure 2.3: Total sulfur content (wt. %) in the Herrin No. 6 coal (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_totals.pdf) 15
Figure 2.4: Ratio of pyritic to organic sulfur in the Springfield No. 5 coal (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfieldpyrstoorgsratio.pdf) 16
Figure 2.5: Ratio of pyritic to organic sulfur in the Herrin No. 6 coal (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_pyrstoorgsratio.pdf) 17
Figure 3.1: Chlorine (%) in U.S. coal (Source: Gluskoter et al, 1977) 21
Figure 3.2: Average chlorine concentrations (%) in Illinois coal by county 21
Figure 3.3: Chlorine content of the Springfield coal in Illinois (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_cl.pdf) 25
Figure 3.4: Chlorine content of the Herrin coal in Illinois (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_cl.pdf) 26
Figure 3.5: Aerial distribution of chlorine in the Herrin coal in Illinois (Source: Bragg et al. 1991) 27
Figure 5.1: Typical water-management flow chart for an Illinois mine complex 40
Figure 5.2: Typical layout of refuse disposal area, sediment pond and NPDES Discharge point 40
Figure 5.3: Distribution of sulfate concentration for Illinois surface and underground mines outfall 42
Figure 5.4: Chloride concentration distribution for discharges from Illinois underground mines 42
Figure 5.5: Chloride concentration distribution for discharges from Illinois surface Mines 43
Figure 5.6: Sulfate concentration vs. precipitation for underground mine #3 44
Figure 5.7: Chloride concentration vs. precipitation for underground mine #4 45
Figure 5.8: Sulfate concentration vs. precipitation for underground mine #10 45
Figure 5.9: Sulfate concentration vs. precipitation for underground mine #6 46
Figure 5.10: Chloride concentration vs. precipitation for underground mine #6 46
Figure 5.11: Sulfate concentration vs. precipitation for underground mine #9 47
Figure 6.1: Mine I aerial photograph 50
Figure 6.2: Mine II aerial photograph 52
Figure 6.3: Mine III aerial photograph 53
Figure 6.4: Mine IV aerial photograph 54
Figure 6.5: Mine V aerial photograph 55
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6</td>
<td>Mine VI aerial photograph</td>
<td>56</td>
</tr>
<tr>
<td>6.7</td>
<td>Mine VII aerial photograph</td>
<td>57</td>
</tr>
<tr>
<td>6.8</td>
<td>Mine VIII aerial photograph</td>
<td>58</td>
</tr>
<tr>
<td>7.1(a) &amp; (b)</td>
<td>Alkaline amendment (agricultural lime) broadcasts</td>
<td>66</td>
</tr>
<tr>
<td>7.2</td>
<td>Alkaline recharge trench</td>
<td>67</td>
</tr>
<tr>
<td>7.3</td>
<td>Refuse reclamation: oxidation management - pyrite oxidation vs. release of alkalinity</td>
<td>69</td>
</tr>
<tr>
<td>7.4</td>
<td>Typical slurry zones of different characteristics in an impoundment</td>
<td>70</td>
</tr>
<tr>
<td>7.5</td>
<td>Slurry processing to reduce pyrite and produce a non-acid soil substitute (Source: Nawrot et al. 1984)</td>
<td>73</td>
</tr>
<tr>
<td>7.6</td>
<td>Example of a mixing zone: flow chart</td>
<td>77</td>
</tr>
<tr>
<td>7.7</td>
<td>Modified water flow circuit: maximize use of onsite dilution source</td>
<td>78</td>
</tr>
<tr>
<td>8.1</td>
<td>Physical and geochemical features of typical slurry zones (Source: Nawrot and Gray, 2000)</td>
<td>81</td>
</tr>
<tr>
<td>8.2</td>
<td>Example of natural slurry zones within a final cut impoundment (source: Nawrot and Gray, 2000)</td>
<td>83</td>
</tr>
<tr>
<td>8.3</td>
<td>Engineered slurry zones within a proposed improved slurry impoundment structure: option 1</td>
<td>84</td>
</tr>
<tr>
<td>8.4</td>
<td>Engineered slurry zones within proposed improved slurry impoundment: option 2</td>
<td>85</td>
</tr>
<tr>
<td>8.5</td>
<td>Sequence of encapsulated pyrite-bearing refuse and clay-rich cover material resulting from the segregated disposal good management practice</td>
<td>86</td>
</tr>
<tr>
<td>8.6</td>
<td>Modified coal processing for production of combined course and dewatered FCPW materials</td>
<td>88</td>
</tr>
<tr>
<td>8.7a</td>
<td>Range diagram for contemporaneous placement of combined coarse and dewatered FCPW materials</td>
<td>89</td>
</tr>
<tr>
<td>8.7b</td>
<td>Improved coal refuse facility with combined course and dewatered FCPW materials and managed slurry impoundments</td>
<td>89</td>
</tr>
<tr>
<td>8.8</td>
<td>Typical 40-ton class articulated dump truck with an ejector bed</td>
<td>90</td>
</tr>
<tr>
<td>8.9</td>
<td>Typical steep-slope compactor (smooth drum version shown)</td>
<td>90</td>
</tr>
<tr>
<td>8.10</td>
<td>Examples of kinetic leach test cells for mine waste studies (source: Lawrence, 1995)</td>
<td>93</td>
</tr>
<tr>
<td>8.11</td>
<td>Diagram of a typical deep cone thickener (Parekh et al., 2005); thickener underflow = feed</td>
<td>95</td>
</tr>
<tr>
<td>8.12</td>
<td>Deep cone thickener setup with addition of paste thickening as suggested by Parekh et al. (2005)</td>
<td>97</td>
</tr>
<tr>
<td>8.13</td>
<td>Segregated refuse CGMP option</td>
<td>98</td>
</tr>
<tr>
<td>9.1</td>
<td>Laboratory version of the developed percolation device</td>
<td>101</td>
</tr>
<tr>
<td>9.2</td>
<td>Volume of percolation vs. time (at varying compaction efforts)</td>
<td>102</td>
</tr>
<tr>
<td>9.3</td>
<td>Rate of percolation and sample height vs. compaction effort</td>
<td>103</td>
</tr>
<tr>
<td>9.4</td>
<td>Field compaction assessment device</td>
<td>104</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The project team acknowledges the financial support of Illinois Environmental Protection Agency (IEPA) and Illinois Clean Coal Institute (ICCI) of the Illinois Department of Commerce and Economic Opportunity for providing funding for this project.

The team also greatly appreciates the input and guidance provided by the following advisory committee members:

Mr. Peter Swenson, USEPA
Mr. Toby Frevert; Mr. Larry Crislip; Mr. Sanjay Sofat; Mr. Bob Mosher, IEPA
Mr. Phil Gonet, Illinois Coal Association
Mr. Eric Fry, Peabody Energy Company
Mr. Steve Phifer, Freeman United Coal Company
Mr. Rick Shellinger, Knight Hawk Coal Company
Mr. Scott Fowler, Illinois Office of Mines and Minerals
Mr. Dan Wheeler, Office of Coal Development
Dr. Ron Carty, Illinois Clean Coal Institute
Ms. Tracy Barkley, Prairie Rivers Network

The cooperation and assistance provided by industry professionals cooperating in this study is sincerely acknowledged. Special thanks go to several mines that provided funding for laboratory testing of their refuse characteristics. The project team also acknowledges the Illinois Department of Natural Resources, Office of Mines and Minerals for providing the mine permit applications data, water quality data and GIS mine viewer data.

The project team thanks Mr. Robert Veto of Standard Laboratories for providing results of refuse and water quality analyses in a timely fashion. Sincere thanks are also due to Mr. Atul Mahajan, a graduate research assistant at SIUC, who worked diligently to prepare the final report manuscript.
ABSTRACT

In the past, Illinois Environmental Protection Agency (IEPA) has regulated mine discharges under the Pollution Control Board's Subtitle D regulations and has required these discharges to comply with sulfate effluent limitation of 3,500 mg/L. More recently, both U.S. Environmental Protection Agency (USEPA) and IEPA have been regulating these discharges under the Subtitle C general use water quality standard of 500 mg/L. Mine operators are therefore looking into alternatives that would help them to comply with the general use water quality standard for sulfate. Since compliance with the general use standard may negatively impact competitiveness of Illinois coal industry, coal professionals and environmental groups are working with IEPA and USEPA to develop a sulfate standard that will be technically sound and environmentally protective. Also, IEPA has allowed mine discharges to comply with chloride effluent limitation of 1,000 mg/L in the past. However, IEPA now requires mine discharges to comply with the Subtitle C general use water quality standard of 500 mg/L.

To assist the coal industry with meeting the evolving standards, this study was aimed to identify good management practices (GMPs) for minimizing sulfate and chloride discharges from Illinois coal mines. The goals were to 1) survey current management practices for controlling sulfate and chloride discharges from mining operations at NPDES locations, 2) assess effectiveness of the identified practices, and 3) develop an inventory of good practices for use and consideration by the coal industry at their specific sites. Study was based on literature review, interviews with professional experts, visits to mining and processing operations, limited laboratory studies and analysis of historical water quality data and water quality data collected during visits to active mining sites. Identified GMPs were divided into two categories: proven good management practices (PGMPs) and conceptual good management practices (CGMPs). The PGMPs’ effectiveness in minimizing sulfate discharges has been field demonstrated in the past. The CGMPs present concepts that are founded on scientific principles that have potential to minimize sulfate discharges but need further development and field demonstration. The study suggests that additional dilution is the only practical approach to comply with reduced chloride standard.
Illinois mining operations discharge sulfate in water at the National Pollutant Discharge Elimination System (NPDES) designated discharge points. It is well recognized that sulfates are primarily generated through oxidation and leaching of pyrite in selected overburden rocks and coal processing waste. As a result of this weathering process, sulfates will be generated regardless of management practices in place. Mining operation permits recognize that some amount of sulfates will be discharged by the mining, processing, and waste management. The permit approval is based on demonstrating that the discharges of sulfate and chloride will be minimized and will meet allowable limits. In the past, IEPA has regulated mine discharges under the Pollution Control Board's Subtitle D regulations and has required these discharges to comply with sulfate effluent limitation of 3,500 mg/L. More recently, both USEPA and IEPA has been regulating these discharges under the Subtitle C general use water quality standard of 500 mg/L. Mine operators are therefore looking into alternatives that would help them to comply with the general use water quality standard for sulfate. Since compliance to the general use standard may negatively impact competitiveness of Illinois coal industry, coal professionals and environmental groups are working with IEPA and USEPA to develop a sulfate standard that will be technically sound and environmentally protective. Also, IEPA has allowed mine discharges to comply with chloride effluent limitation of 1,000 mg/L in the past. However, IEPA now requires mine discharges to comply with the Subtitle C general use water quality standard of 500 mg/L.

The Advent Group, Inc (2005) performed a study to evaluate the cost impact of reducing the current 3,500 mg/L sulfate effluent limitation for Illinois mines to 500 mg/L general use standard. The data for analysis was collected from IEPA, and some of the data is from non-active but permitted sites.

- Eighty eight NPDES permits were reviewed that included 268 outfalls.
- Of these 16% had sulfate concentrations greater than 2,500 mg/L, while 37% had sulfate concentration in the 500 to 2,000 mg/L range.
- The average sulfate concentration for all outfalls was 621 mg/L.
- Compliance to 500 mg/L sulfate standard will have a major economic impact on Illinois coal mines by significantly increasing the cost for operating coal mines. They assessed the difference in cost impact to the industry if the sulfate standard was increased from 500 mg/L to 2,000 mg/L. For this analysis, two technologies were considered: 1) addition of an excessive amount of hydrated lime for precipitation of sulfate down to 2,000 mg/L followed by addition of hydrochloric acid for pH adjustment, and 2) application of caustic/nano-filtration system for compliance with 500 mg/L standard.
- Over a ten-year period, the cost to comply with 500 mg/L standard will be 7.5 billion dollars for affected Illinois coal mines. Over the same period, the cost to comply with 2,000 mg/L standard will be 730 million dollars.
- An analysis of sulfate concentration in surface monitoring stations in Illinois indicated: 1) about 2.8% of the points had an average concentration above 500
mg/L, while 12.4% had maximum sulfate concentrations above 500 mg/L, and 2) about 7.3% of the points had maximum sulfate concentration about 2,000 mg/L.

A similar analysis of 3,080 individual chloride concentrations data (Crislip, 2005) indicated the following.

- About 4.7% of samples exceeded 1,000 mg/L, while an additional 1.8% of the samples ranged 750–1,000 mg/L.
- Of the 73 facilities, where the above samples were collected, 9 facilities exceeded 1,000 mg/L and 13 facilities had chloride concentrations in the range 750–1,000 mg/L.

The observations above suggested that before implementing any treatment approach to reduce sulfate concentrations, attempts should be made to minimize sulfate discharges through implementation of good operations management practices that are significantly lower cost and would have minimal side effects of using chemical treatment practices. Therefore, this study was initiated to identify and assess good management practices (GMPs) for minimizing sulfate and chloride discharges from coal mines. Their implementation should reduce water treatment cost (that can be technically challenging and cost prohibitive) and minimize the negative impacts of implementing any new sulfate standards less than 3,500 mg/L. The goals of this study were to 1) survey coal processing waste (coal refuse) management practices for controlling sulfate and chloride discharges from mining operations at NPDES locations, 2) assess effectiveness of the identified practices, and 3) develop an inventory of GMPs that can be considered by operators on a site specific basis to develop best management practices (BMPs).

The overall study was performed through 1) pertinent literature review, 2) questionnaire and personal interview data collection and data analysis from selected organizations and professionals throughout USA, with emphasis on adjoining high sulfur coal mining states, 3) survey of selected mining, processing and waste management operations in Illinois for review of management practices for sulfate and chloride control, 4) analysis of historical water quality data and water quality data collected during visits to surveyed mine sites to correlate management practices and water quality, 5) identification of management practices that pointed toward lower discharge of sulfates and chlorides, 6) identification of good management practices with high commercial potential based on professional judgment and input from peers, and 7) development of recommendations for good management practices in the area of pre-mining characterization, permitting process requirements, mining and reclamation operations, and monitoring and control requirements.

The GMPs were divided into two categories: proven good management practices (PGMPs) and conceptual good management practices (CGMPs). PGMPs are proven practices and their use and effectiveness is well documented in Illinois or elsewhere. Examples of such practices include 1) minimize period of weathering and oxidation...
of overburden and coal processing waste to less than 12 months based on their geochemistry and local temperature and precipitation environment, 2) contemporaneous reclamation to the extent possible to minimize large areas susceptible to oxidation and acidification, 3) appropriate compaction of coarse waste, 4) minimizing the formation of deltas of pyrite-rich slurry fines exposed above the water table and capillary zone through the application of movable, low scouring slurry discharge points. The project team believes that careful implementation of PGMPs can assist mine operators in Illinois to improve upon current high sulfate discharge concentrations in some mines. CGMPs on the other hand are founded on sound scientific principles but require additional development and field demonstration. The project team believes that CGMPs should be further developed through additional research and development. These have the potential to significantly minimize long-term liability of mine operators for water treatment and environmental damage. The project team also believes that permit application should include 1) additional geochemical characterization of coal seam and immediate roof and floor strata during pre-mining phase to assess potential for excessive sulfate and chloride discharge, 2) utilize the above data to plan waste and water management operations to achieve desired discharges to the extent possible, 3) discussion of how the mine operator plans to utilize GMPs to minimize sulfate and chloride discharges, 4) additional geochemical characterization of different fractions of coal processing waste (as it comes out of the processing plant) to support or modify planning of waste management operations from pre-mining phase, 5) discussion of the steps that the operator plans to take to minimize sulfate and chloride discharges, and 6) periodic discharge of water and use of mixing zones where chloride concentrations are expected to be high.

** The term “coal refuse” refers to coal processing waste and reject from rotary breakers prior to the run-of-mine (ROM) coal entering the processing plant. Coal refuse consists of typically two fractions: 1) coarse coal processing waste (CCPW), generally larger than 100 mesh (150 micron) size or in some cases larger than 1/8 inch size, and 2) fine coal processing waste (FCPW) or slurry generally less than 100 mesh sizes. These terms are used throughout this report and sometimes interchangeably.
CHAPTER 1
INTRODUCTION AND BACKGROUND

1.1 Background

Coal mine operations across Illinois generate sulfates and chlorides during coal mining, coal processing and waste disposal processes, which often have to be discharged outside the mine permit boundary. In the past, Illinois Environmental Protection Agency allowed mine discharges to comply with sulfate standard of 3,500 mg/L, whereas the general use water quality standard was 500 mg/L. In a review of current regulations over the last few years, U.S. Environmental Protection Agency (USEPA) and IEPA agreed that separate sulfate effluent limitation for the same designated use waters were not legally defensible, and that the coal mine discharge specific effluent limitation should be eliminated. Compliance to the general use standard of 500 mg/L (if implemented) will negatively impact competitiveness of Illinois coal mines. Coal industry professionals, through Illinois Coal Association, and environmental groups such as Prairie Rivers and Sierra Club have been working with IEPA and USEPA to develop sulfate standards that will be technically sound and environmentally protective. Sulfate standard of about 2,000 mg/L based on water hardness is currently being debated for rulemaking and implementation.

Current Illinois’ general use standard for chlorides is 500 mg/L. In the past, IEPA allowed mine discharges to comply with chloride effluent limitation of 1,000 mg/L. Some mining facilities in the State are not able to meet this limitation occasionally. Similar to sulfate standards, discussions are currently underway to implement general water use chloride standard of 500 mg/L.

The Advent Group, Inc (2005) performed a study to evaluate the cost impact of changing sulfate standards for mining industry in Illinois. The analysis was based on NPDES permits data collected from IEPA that included some data from non-active permitted sites.

- Eighty eight NPDES permits were reviewed that included 268 outfalls.
- Of these 16% had sulfate concentrations greater than 2,500 mg/L, while 37% had sulfate concentration in the 500 to 2,000 mg/L ranges.
- The average sulfate concentration for all outfalls was 621 mg/L.
- Compliance to 500 mg/L sulfate standard will have a major economic impact on Illinois coal mines by significantly increasing the cost for operating coal mines.

**** The term “coal refuse” refers to coal processing waste and reject from rotary breakers prior to the run-of-mine (ROM) coal entering the processing plant. Coal refuse consists of typically two fractions: 1) coarse coal processing waste (CCPW) generally larger than 100 mesh (150 micron) sizes; in some cases larger than 1/8 inch, and 2) fine coal processing waste (FCPW) or slurry
generally less than 100 mesh (150 micron) sizes. These terms are used throughout this report and sometimes interchangeably.

- They assessed the difference in cost impact to the industry if the sulfate standard was increased from 500 mg/L to 2,000 mg/L. For this analysis, two technologies were considered: 1) excess lime and hydrochloric acid for precipitating the sulfate down to 2,000 mg/L, and 2) caustic/nano-filtration system for compliance with 500 mg/L standard.
- Over a ten year period, the cost to comply with 500 mg/L standard will be 7.5 billion dollars for affected Illinois coal mines. Over the same period, the cost to comply with 2,000 mg/L standard will be 730 million dollars.
- An analysis of sulfate concentration in surface monitoring stations in Illinois indicated: 1) about 2.8% of the points had an average concentration above 500 mg/L, while 12.4% had maximum sulfate concentrations above 500 mg/L, and 2) about 7.3% of the points had maximum sulfate concentration about 2,000 mg/L.

A similar analysis of 3,080 individual chloride concentrations data (Crislip, 2005) indicated the following.

- About 4.7% of samples exceeded 1,000 mg/L, while an additional 1.8% of the samples ranged 750–1,000 mg/L.
- Of the 73 facilities, where the above samples were collected, 9 facilities exceeded 1,000 mg/L and 13 facilities had chloride concentrations in the range 750–1,000 mg/L.

1.2 Problem Statement

Based on input from all stakeholders during 2006, IEPA has submitted recommendations to Illinois Pollution Control Board for rulemaking on sulfate and chloride discharges that would be significantly less than those allowed in the past. To assist industry meet those guidelines with minimal impact, Illinois Coal Association (ICA) and IEPA identified the need to: 1) Survey state-of-the-art practices in sulfate and chloride discharge control in Illinois mines, and 2) Identify and develop good management practices (GMPs) to minimize sulfate and chloride discharges from Illinois mining operations and meet stipulated standards.

1.3 Significance of Study

This study was instituted to identify the good management practices (GMPs) for coal refuse management practices for minimizing sulfate and chloride discharges. As stricter sulfate and chloride discharge standards are going to increase the cost of coal mining in Illinois, this study aims to provide the coal industry with alternatives for good practices that should help reduce the sulfate and chloride discharge levels. Their implementation should also reduce the need for water treatment. As presented by the Advent Group, Inc. (2005), which looked at two sulfate treatment technologies, the cost can be very high. The first technology used lime and hydrochloric acid to
achieve a limit of 2,000 mg/L and was found to cost the Illinois coal industry $730,000,000 over a ten year period. The second technology was based on a caustic neutralization and nano-filtration system to achieve a limit of 500 mg/L and would cost the Illinois coal industry $7,500,000,000 over a ten year period. New, lower cost technologies are emerging such as passive and semi-passive anaerobic bioreactors that employ sulfate-reducing bacteria (SRB) to biologically treat high sulfate waste streams. However, the commercial use of these technologies is not fully available at this time. Therefore, the suggested GMPs should reduce the negative economic impacts of implementing any new sulfate and chloride standards.

1.4 Scope of Study

The study scope included active surface and underground coal mines, processing plants and coal refuse disposal areas in Illinois. The goals of this study were to 1) identify good management practices for controlling sulfate and chloride discharges from mining operation at NPDES locations, 2) assess which of the identified practices will be most effective in the field from environmental and economics points of view, and 3) identify approaches to predict sulfate and chloride discharge through pre-mining studies.

Although the original proposal used the term “Best Management Practice” or BMP, the authors believe that the term is not justified because a BMP at one site may not be a BMP at another location due to variations in hydrogeology and mining conditions. The authors believe that a more appropriate term is “Good Management Practice” or GMP. A GMP is based on sound scientific principles and experience in the field at different locations. Mine operators may experiment with GMPs (or use others’ field experience) to develop BMPs for their own site. At the same time the authors recognize that the identification and application of a mine specific BMP creates additional burden on regulators during the permit review process.

1.5 Experimental and Study Procedures

The overall study was performed through: 1) pertinent literature review, 2) questionnaire and personal interview data collection and data analysis from selected organizations and professionals throughout USA, with emphasis on adjoining high sulfur coal mining states, 3) survey of selected mining, processing and waste management operations in Illinois for review of management practices for sulfate and chloride control, 4) analysis of historical water quality data and water quality data collected during visits to surveyed mine sites to correlate management practices and water quality, 5) identification of management practices that point toward lower discharge of sulfates and chlorides, 6) identify best management practices with high commercial potential based on professional judgment and economics, and 7) developing recommendations for GMPs in the area of pre-mining characterization, permitting process and requirements, mining and reclamation operations, and monitoring and control requirements. These tasks are discussed in more detail in the main sections of the proposal. The results of this study may lead to field
demonstration of selected recommendations for commercial implementation. The overall research program is outlined in the attached flow chart in Figure 1.1.

Figure 1.1. Flow chart for the present study.

To ensure input from stakeholders throughout the study, an advisory committee was formed that met quarterly to review project progress and plans for the following quarter. The advisory committee membership is given below.

USEPA - Mr. Peter Swenson, Region V

IEPA - Mr. Toby Frevert
- Mr. Larry Crislip
- Mr. Sanjay Sofat
- Mr. Bob Mosher

ICA - Mr. Phil Gonet

Illinois Coal Industry - Mr. Eric Fry (Peabody Energy Company)
- Mr. Steve Phifer (Freeman United Coal Company)
- Mr. Rick Shellinger (Knight Hawk Coal Company)

Illinois Office of Mines and Minerals - Mr. Scott Fowler

Office of Coal Development - Mr. Dan Wheeler
Illinois Clean Coal Institute - Dr. Ron Carty
Prairie Rivers Network - Ms. Tracy Barkley

Three (3) advisory committees were held during the course of this study: May 31, 2006, September 7, 2006, and February 9, 2007. The project team also sought input from experienced mining and environmental professionals in Illinois throughout the study. Particular thanks are due to Misters Eric Fry, Grady White, Jay Honse, Phil Davis, Ron Pickering of Peabody Energy, and Misters Larry Crislip (IEPA) and Scott Fowler (Office of Mines and Minerals). In addition, in person and telephone conversations were held with Mr. Keith Brady and his staff from Pennsylvania Department of Environmental Protection, Dr. Paul Ziemkiewicz of West Virginia University, and Robert Kleinman of the U.S Department of Energy, among others.

The project team for the study consisted of following professionals:

Dr. Y.P. Chugh - Principal Investigator
Mr. Samrat Mohanty - Mining and geotechnical engineering (Project Coordinator)
Mr. Paul Behum - Geochemistry, groundwater hydrology, refuse management practices.
Mr. Jack Nawrot - Refuse management, geochemistry, water quality
Mr. Bill Bell - Mining and coal processing operations experience

The project team met each week to discuss various aspects of the study to keep it on schedule. Mr. Larry Crislip of IEPA was invited to attend several of these meetings to incorporate IEPA input into planning and conduct of the study.

1.6 Report Organization

This report is organized into ten (10) chapters. Chapters 2 and 3 review pertinent literature related to “Sulfate and Chloride Generation and Control”. Chapter 4 analyzes “Available Water Quality Data”, Chapter 5 summarizes findings of “Permit Applications Review”, and Chapter 6 discusses “Field Visits and Findings”. Chapter 7 briefly describes “Proven Good Mining Practices” and Chapter 8 describes “Conceptual Good Mining Practices”. Chapter 9 describes “Development of Field Compaction Assessment Device”, and Chapter 10 summarizes “Miscellaneous Recommendations”.
CHAPTER 2
REVIEW OF PERTINENT LITERATURE: SULFATE DISCHARGES

2.1 Introduction

Sulfate discharge is a very common occurrence from mine waste rocks, tailings, and from mine structures such as surface mines and underground workings. Acid mine drainage (AMD) and associated pollutants may be generated during the mining and processing of coal and has been described by a number of researchers as the most important environmental issue facing the U.S. coal and metal mining industries (Lapakko, 1993; USDA Forest Service, 1993). The process essentially refers to chemical alteration of water quality as it comes into contact with pyrite minerals present in rocks in the presence of air. Sulfate discharges typically accompany the generation of AMD. On the other hand chloride discharges are most likely derived from the liberation of both saline ground water and from chloride ions weakly bonded to hydrogen within coal maceral (organic “mineral”) micropores. Due to these differences sulfate and chloride discharges may be geochemically independent of each other. Since significant amount of chlorine is present in Illinois coal in addition to pyrite, there is potential for both chloride discharge as well as sulfate discharge due to AMD generation. Both of these anions are considered “conservative” in the environment, that is, they are not easily attenuated naturally.

2.2 Sulfate Discharge in Coal Mines

AMD is characterized by low pH (high acidity) and high iron content. Frequently, AMD contains abnormally high concentrations of other metals, which for coal mining discharges include manganese and aluminum. The principal cause of AMD is the weathering of the iron sulfide minerals (pyrites), which commonly occur in coal and the associated strata. Of concern to this study is the parallel release of the anion “sulfate” during the process of the liberation of hydrogen and metal ions. AMD is primarily an issue at abandoned mine lands and pre-law operations, resulting from inadequate reclamation practices. However, with the enactment of SMCRA, mine operations are subject to strict performance standards that prevent and minimize AMD formation.

In Illinois, AMD has been associated with coal mining before the advent of environmental legislation in the 1970’s. Although AMD can be found throughout the State, this issue has historically been a concern in southern Illinois due, in part, to geologic factors. AMD occurs where mineral and proton acidity combined exceeds naturally available alkalinity. It typically contains elevated concentrations of sulfate (SO$_4^{2-}$). AMD may or may not have a low pH (high concentration of H$^+$ ions). Again, the major source of acidity is oxidation of the mineral pyrite (FeS$_2$) in freshly mined rock that is exposed to air and water. Pyrite oxidation can occur rapidly upon exposure to humid air or aerated water and is aided by bacterial activity.

Sulfate is not a National Pollutant Discharge (NPDES) parameter. But, it is an excellent marker or indicator of AMD generation. Sulfate is regulated by the State of
Illinois under Title 35, Subpart C, Part 304 (State of Illinois, 1988) or Title 35, Subpart C, Part 406 (State of Illinois, 1987). There is, however, a National Secondary Drinking Water sulfate standard of 250 mg/L that is usually applied to groundwater aquifers and surface water intakes.

2.3 Geochemistry of AMD and Sulfate Production

The geochemistry of AMD is based on the interactions of iron sulfide minerals with oxygen, water, and bacteria. The iron sulfide minerals pyrite (FeS₂) and marcasite (FeS₂) are the principal sulfur-bearing minerals in bituminous coal. Pyrite is distributed in coal and overburden rocks, especially in shale of marine and brackish water origin. Because of this pyrite is recognized as the major source of natural and mine-generated acidic drainage and acid soils. The overall stoichiometric reaction describing the oxidation of the minerals pyrite and marcasite are commonly given as:

\[
\text{FeS}_2 (s) + 3.75 \text{O}_2 + 3.5 \text{H}_2\text{O} = \text{Fe(OH)}_3 (s) + 2 \text{SO}_4^{2-} + 4 \text{H}^+ + \text{heat} \quad (2.1)
\]

In reaction 2.1, solid pyrite, oxygen (O₂) and water (H₂O) are reactants, and solid ferric hydroxide (Fe(OH)₃), sulfate (SO₄²⁻), hydrogen ions (H⁺) and heat energy are products. It is important to note that for every mole of pyrite (FeS₂) two moles of sulfate are released. In many samples collected of coal mine drainage, an abundance of dissolved, reduced form ferrous iron (Fe²⁺) indicate that the chemical reactions are at an intermediate stage (partially oxidized) in the series of reactions that upon completion forms the process known as pyrite oxidation (reaction 2.1). Pyrite oxidation is an exothermic reaction because the net reaction produces heat. The following reactions list the individual stages in the completion of that reaction (Stumm and Morgan, 1981, pp. 470):

\[
\text{FeS}_2 (s) + 3.5 \text{O}_2 + \text{H}_2\text{O} = \text{Fe}^{2+} + 2 \text{SO}_4^{2-} + 2\text{H}^+ \quad (2.2)
\]

\[
\text{Fe}^{2+} + 0.25 \text{O}_2 + \text{H}^+ = \text{Fe}^{3+} + 0.5 \text{H}_2\text{O} \quad (2.3)
\]

\[
\text{FeS}_2 (s) + 14 \text{Fe}^{3+} + 8 \text{H}_2\text{O} = 15 \text{Fe}^{2+} + 2 \text{SO}_4^{2-} + 16 \text{H}^+ \quad (2.4)
\]

\[
\text{Fe}^{3+} + 3 \text{H}_2\text{O} = \text{Fe(OH)}_3 (s) + 3 \text{H}^+ \quad (2.5)
\]

In reaction 2.4, dissolved ferric iron (Fe³⁺) produced by reaction 2.3 is the oxidizing agent for pyrite that releases sulfate. Kinetic studies have shown that at an acidic pH, rates of pyrite oxidation by Fe³⁺ are much faster than oxidation by O₂ (reaction 2.2). Therefore, in well-established acid-generating environments, the typical sequence is pyrite oxidation by Equation 2.4 to produce Fe²⁺, which is then oxidized to Fe³⁺ by bacteria via reaction 2.3; the Fe³⁺ being a powerful oxidant is then available for further pyrite oxidation. Note that, although O₂ is not directly consumed in the Fe³⁺ pyrite-oxidizing step, it is still necessary for the continued regeneration of Fe³⁺ to continue the pyrite-oxidation cycle. Because of the relative insolubility of Fe³⁺ (ferric iron), most dissolved iron in solutions with pH greater than about 3.5, occurs as
ferrous iron ($Fe^{2+}$). Ferric iron will occur in AMD as a series of species, including $Fe^{3+}$, $FeOH^{2+}$, $Fe(OH)_2^+$, and $Fe(OH)_3$. To represent all of these species the Roman numeral (III) is used, reporting all ferric species as Fe (III). Similarly Fe (II) is used to denote all of the ferrous iron species.

Reactions 2.2 and 2.3, which involve the oxidation of sulfur and iron by gaseous or dissolved $O_2$, can be mediated by various species of sulfur and iron-oxidizing bacteria, notably those of the genus *Thiobacillus*. These bacteria require only dissolved $CO_2$ and $O_2$, a reduced form of Fe or S, and minor N and P for their metabolism. Site-specific strains of bacteria, normally *Thiobacillus ferrooxidans*, utilize the sulfur contained in the pyrite as a source of energy. These bacteria are autotrophic, that is they obtain their nutritional needs from the nitrogen, oxygen, carbon dioxide and water in an atmospheric environment and from minerals containing sulfur and phosphorus. Although these bacteria are not true catalysts by definition, they do act as accelerating agents if the conditions of their habitat are at or close to optimal conditions. Because of this, *Thiobacillus ferrooxidans* is an important factor in the generation of AMD. However, it is not the only species of importance. Bacteria are great cooperators and work as a community with the waste products from one species being used for another. This cooperative web of life exists deep beneath the surface and certainly within spoil and processing waste rock piles that are exposed to weathering. Some species like *Thiobacillus ferrooxidans*, are oxygen-loving and will exist in the zone of aeration above the water table, while others are anoxic, like *Desulfovibrio desulficans* and live below the water table or in anoxic wetlands.

2.4 Common Sulfate Sources

There are multiple sources of sulfate generation in a coal mine environment. These sources are presented more or less in order of importance for the Illinois coal basin.

(i) Conventional weathering of pyrite: Sulfate discharges during coal mining and associated processes are formed when sulfide minerals present in coal and associated strata are exposed to oxidizing conditions. The most common sulfide minerals in coal are pyrite and marcasite. The sulfide minerals will oxidize in the presence of oxygen and water to form highly acidic, sulfate-rich discharge. The following chemical reactions seem to govern the chemical transformation (Skousen and Ziemkiewicz, 1995). Iron sulfide ($FeS_2$) is oxidized initially to form ferrous iron, sulfate, and acidity. Ferrous iron may be oxidized to form ferric iron. Ferric iron may then directly attack pyrite and work as a catalyst to develop large amounts of ferrous iron, sulfate, and acidity. The generation of acid mine drainage (AMD) and associated sulfate may be controlled if water and/or oxygen access to sulfide minerals is controlled. Chemical conversion of ferrous iron to ferric iron is extremely slow. However, presence of iron-oxidizing bacteria increases the rate of reaction and, as a consequence, the production of sulfates as much as million times greater (Singer and Stumm, 1970).
Dissolved oxygen concentration, temperature, pH of water, reactive surface area of pyrites, form of pyrite, catalytic agents, flushing frequencies and time allowed are some of the parameters that control rate of the pyrite oxidation and sulfate discharge process. The inherent amount of pyrite within the coal and the associated strata is an important factor when the source of the runoff is coal stockpiles and coal processing waste.

Geologically, sediments deposited in a marine paleo-environment, containing organic matter, under reducing conditions usually favor the formation of sulfides. Thus bituminous coals and associated dark, carbonaceous shales tend to contain larger amounts of sulfur as pyrite. The physical structure of the pyrite plays a significant role in the level of sulfate discharge. For example, marcasite and frambooidal pyrites oxidize quicker than coarse, crystalline forms of pyrite. Also, it has been observed that fine-grained pyrites yield larger acid and sulfate discharge (Skousen and Ziemkiewicz, 1995). Presence of carbonates plays a vital role in inhibiting pyrite oxidation, including sulfate formation (Brady et al., 1998).

(ii) Oxidation of pyrite by ferric iron: In an acid-generating environment, the typical sequence is pyrite oxidation to produce ferrous iron, Fe\(^{2+}\), which is, subsequently, oxidized to ferric iron, Fe\(^{3+}\), by bacteria such as *Thiobacillus ferrooxidans*. The Fe\(^{3+}\) is then available for further pyrite oxidation. As shown in reaction 2.5, two moles of sulfate are released for every mole of pyrite oxidized. Although O\(_2\) is not directly consumed in the Fe\(^{3+}\) pyrite-oxidizing step, it is necessary for the regeneration of Fe\(^{3+}\) to continue the pyrite-oxidation cycle.

(iii) Mobilization of Sulfate from Secondary Iron-bearing Minerals: Secondary sulfate minerals are created though evaporation (drying or dehydration) of an AMD waste stream. Sulfate minerals are only temporarily stable during periods of drying and then dissolve in water following precipitation/infiltration events. One of these minerals is Jarosite, an oxyhydroxysulfate mineral [(K,Na,H)Fe\(_3\)(SO\(_4\))\(_2\)(OH)\(_6\) (variable)]. Jarosite is the main secondary mineral of iron that forms under highly acidic (pH < 3.5) and oxidizing conditions. When these conditions change (i.e. more alkaline conditions are established by a change in the hydrology), the mineral will be converted to ferrohydrate (known as “yellow boy” in mining terms) and ultimately a more stable and compact mineral Geothite, which is a form of iron ore. However, what is most important for this study is that the sulfate contained within the Jarosite structure is mobilized. Similarly, other minerals such as Schwertmannite [Fe\(_8\)O\(_9\)(OH)\(_6\) (SO\(_4\)) (variable)], the main form of Fe under moderately acidic (pH > 3.5 < 5.0 S.U.) and oxidizing conditions will convert to more stable iron minerals and free sulfate. The acidity temporarily stored as sulfate minerals is known as “stored” acidity. The cycle of drying and then sudden release of the acidity and sulfate from sulfate minerals during rainfall events is reflected in the surges of acidity and sulfate release observed at AMD sites (Hornberger and others, 1981; Hornberger, 1985; and Smith, 1988). The four primary equations (2.2 thru 2.5) shown earlier in this section show that the products of pyrite oxidation consist principally of ferric hydroxide, acid (H\(^+\) ions) and sulfate. A number of secondary minerals may form during the weathering of
coal mine overburden and refuse materials. These sulfate minerals are usually present as secondary weathering products of pyrite oxidation. Nordstrom (1982) details the sequence these minerals are formed. Many secondary sulfate minerals have been identified that are typically very soluble and transient in the humid eastern United States. These minerals form during dry periods and under the right conditions their component elements and compounds can be flushed into the surface and ground water systems during precipitation events. The sulfate minerals that contain iron, aluminum, or manganese represent essentially stored acidity and will produce acid when dissolved in water. In most cases, sulfate (a conservative compound) remains in solution and serves as a very good indicator of the amount of pyrites oxidized. Additional information about sulfate minerals occurring as coal mining-related weathering products is found in Cravotta (1994), Lovell (1983), Rose and Cravotta (1998), and Brady and others (1998).

(iv) Mobilization of sulfate inherent in Illinois Basin coals: Three forms of sulfur are present in coal: organic, pyritic and sulfate sulfur. Organic sulfur is bound as it is in living plant tissue to the organic structure and as such is not readily mobilized in the environment. Pyritic sulfur as previously discussed is readily mobilized and as such forms a major contributor to sulfate discharges. Sulfate sulfur occurs as natural minerals that develop as pyrite weathering products within coal and associated carbonaceous rocks in the near surface environment or as minerals that are deposited in the cleats and pores of the coal by ground water. Gluskoter et al. (1977) report the analysis of the sulfur forms in U.S. coals and found that samples from Iowa, Kentucky and Ohio showed the highest percent of the sulfate form of sulfur (Figure 2.1). In general, Illinois coal beds contain a relatively low amount of sulfate sulfur (Gluskoter and Simon, 1968; Gluskoter and others, 1977; Figure 2.1). The amount of the sulfate form in coal increases with weathering and is more readily mobilized when exposed to weathering around the coal outcrop or open mine pit.

Figure 2.1. Sulfate occurrences in U.S. coals (Gluskoter and others, 1977).

(v) Mobilization of sulfate from carbonate minerals: The mineral gypsum [CaSO₄ * H₂O] is stable where Ca²⁺ and SO₄²⁻ are supersaturated. However, due to the moderately high solubility of this mineral, sulfate can remobilize by two methods: 1) where a lower concentration gradient is developed, such as due to dilution by
recharge water with a low ionic strength, and 2) by the “ion pairing effect”. The ion pairing effect occurs wherever there is an abundance of ions, which readily form compounds with Ca$^{2+}$ and SO$_4^{-}$ introduced to the mine environment where the sulfate is “stored” as gypsum. Ions, which form ion pairs with gypsum, include both the cation magnesium, Mg$^{2+}$, and anion chloride, Cl$. Both ions are commonly associated with coal mining facilities in the Midwest, and their presence will create a geochemical condition where the ion pairing effect can occur. As a result, the solubility of gypsum is increased above the normal conditions, thereby, releasing the “stored” sulfate.

Another possible source of sulfate from washed coal and fresh coal waste materials is gypsum that forms during desiccation of these materials in stockpiles and refuse areas. In most cases the water used in the coal processing plant (coal washing) is high in sulfate and chloride, as well as high in hardness (high amounts of calcium and magnesium). These conditions are appropriate for the formation of gypsum coatings on the coal refuse and stockpiled coal particles that can be released upon rewetting by the processes described above. Other sulfate sources are from gypsum (or the mineral anhydrite) that are present in high sulfate coal combustion byproducts (CCBs) such as wet flue gas desulfurization (FGD) sludge and fluidized bed combustion (FBC) byproducts. These are either stored at mine sites as structural fills or used for beneficial purposes to mitigate AMD conditions.

2.5 Characteristics of Illinois Coals

The coalfields of Illinois form a part of the eastern region of the Interior Coal Province, known as Illinois Basin. About 36,800 square miles in Illinois are underlain by the coal-bearing Pennsylvanian system. This represents one of the largest single deposits of bituminous coal in the world (U.S. Geological Survey, 2002). The presence of sulfur in Illinois coal is determined by the character of the strata overlying the coal. Typically, the coal seams are overlain by strata of marine origin, such as marine black fissile shale (carbonaceous shale) or limestone. The total sulfur content of the coal below such strata normally ranges from 3 to 5%. In certain areas, non-marine, silty-gray shale units lie directly above the coal. These formations are considered overbank deposits that occur when the coal swamp was flooded and filled with sediments from a nearby deltaic stream. Where the non-marine gray shale exceeds about 20 ft in thickness, the sulfur content generally is less than 2.5%, and commonly averages 1.5%. Many coal seams also report thin pyrite bands within the coal seam. Overall, the total sulfur content of Illinois coals has been reported from as low as 0.5% to more than 7%. The Springfield (No. 5) and Herrin (No. 6) are the two major coal seams in Illinois coal basin. The presence of total sulfur in the above-mentioned coal seams is depicted in Figures 2.2 and 2.3. The coal resources, where the sulfur content of the coal is less than 2.5%, is estimated to be only about 6% of the remaining Illinois resources. Whereas the organic sulfur content of Illinois coals varies from a minimum of about 0.4% to a maximum of about 3%, pyritic sulfur varies greatly from nearly zero up to 5%. The ratio of pyritic sulfur to organic sulfur in the two seams is presented in Figures 2.4 and 2.5. Sulfate sulfur constitutes a
negligible amount. The average sulfate concentration of 40 Herrin (No. 6) coal seam samples from the Illinois Basin is 0.098% with a standard deviation of 0.162% (Gluskoter et al., 1977). Illinois coal also has a range of mineral matter, which may act as neutralizing agents during pyritic sulfur oxidation process. The amounts of major mineral constituents are presented in Table 2.1. They vary widely over the coal basin both from seam to seam and geographically.

Table 2.1. Median and range of minerals in Illinois coal.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Herrin Coal</th>
<th>Springfield Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay minerals</td>
<td>9.4 (5 - 13.5)</td>
<td>7 (3 - 13)</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.4 (1 - 3.8)</td>
<td>2.4 (1.2 - 4.3)</td>
</tr>
<tr>
<td>Pyrite</td>
<td>3.4 (1 - 11.6)</td>
<td>3.9 (0.5 - 18)</td>
</tr>
<tr>
<td>Calcite</td>
<td>1.3 (0.3 - 5.2)</td>
<td>1.6 (0.3 - 4.9)</td>
</tr>
</tbody>
</table>

Source: Illinois State Geological Survey

2.6 Other Geochemical Factors Associated with Sulfate Generation

(i) Acidity/Alkalinity: By definition acidity is the measure of the base neutralization potential capacity of a volume of water. There are three types of acidity present in most natural waters i.e., proton acidity (free H\(^+\) ions), mineral acidity (associated with dissolved metals), and organic acidity (associated with dissolved organic compounds). AMD is generally low in organic acidity as there is normally little dissolved organic carbon. Total acidity in AMD, therefore, is composed of proton acidity (free protons or low pH) plus metal acidity primarily derived from dissolved Fe, Mn and Al. In most cases, total acidity can be estimated by using the pH and concentration of the dissolved metal ions (converted to milliequivalents). As acidity facilitates AMD generation, it also increases the sulfate generation process.

Alkalinity is a measure of the ability of a volume of water to neutralize the acid. Acidity and alkalinity are not mutually exclusive. Both acidity and alkalinity must be measured and compared. Where acidity exceeds alkalinity the water is said to be Net Acidic. Where the alkalinity exceeds the acidity the water is Net Alkaline. If the pH of AMD is > 4.5 it has some acid neutralization capability and, therefore, has some alkalinity. Alkalinity will attempt to neutralize the metal acidity and to buffer changes in pH. In the process the availability of alkalinity restricts AMD formation and sulfate mobilization. Net Alkaline water has sufficient alkalinity to neutralize the metal acidity.

(ii) Oxygen Availability: The availability of oxygen is vital to the oxidation of pyrite in the oxidation of ferrous (Fe\(^{2+}\)) iron to ferric (Fe\(^{3+}\)) iron. Therefore, where pH < 3.2 an open system with O\(_2\) replenishment must be present (note again that Ferric iron can also oxidize pyrite and generate hydrogen ions), but again O\(_2\) must be present to continually oxidize ferrous to ferric iron (reaction 7). Oxygen transportation in coal refuse disposal areas takes place in two different modes, i.e. advection and diffusion. Oxygen advection in a coal refuse pile refers to its bulk movement due to differential
gas pressures, which may be caused by temperature gradients, barometric pressure differences and wind action (Miller 1997). Advection is greatly controlled by the permeability of the refuse, more specifically surface permeability of the refuse pile. During the oxygen diffusion process, pyritic oxidation consumes the oxygen trapped in the pore spaces of the refuse pile and the change in pore oxygen concentration sets up an oxygen concentration gradient, which leads to diffusion of oxygen from the atmosphere into the refuse pile (Miller, 1997). Water acts as a barrier to the diffusion process. Advection and diffusion of oxygen in the refuse pile may take place together with advection processes complementing the diffusion processes by providing oxygen (Garvie et al., 1997).

(iii) Mineralogical Factors: Different acid-producing minerals present in coal refuse have different reaction rates and acid generation potential. Researchers have tried to come up with relative reaction rates for various sulfide bearing minerals (Jambor and Blowes, 1998), both in the laboratory and in the field. But, pyrites are the most predominant sulfide species from coal refuse acidification point of view. Research has also been conducted on neutralizing minerals for reaction rates and neutralization potential (Lawrence and Wang, 1997). Given equal amounts of acid-producing and neutralizing minerals, net acid and sulfates will be generated since reaction rates of acidification exceed those of neutralization. Unlike pyrite oxidation, which has basically no solubility constraints, the rate of alkalinity production proceeds slower with significant restraints. Two general classes of minerals are involved in alkaline production: carbonates and silicates.

Typically, coal refuse with larger percentage of pyrite will generate more acid than refuse with lesser amount of pyrite. Crystal morphology of pyrites in coal refuse also dictates the acid and sulfate generation potential. Pyrites present in coal sequences are sedimentary by deposition and have been found to be more reactive than hydrothermal pyrites, owing to their unique crystal structure (Rose and Cravotta 1998). Framboidal pyrites found commonly in coal are fine grained and highly reactive due to their larger surface area.
Figure 2.2. Total sulfur content (wt. %) in the Springfield No. 5 coal (Source: http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_totals.pdf).
Figure 2.3. Total sulfur content (wt. %) in Herrin No. 6 coal (Source: http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_totals.pdf).
Figure 2.4. Ratio of pyritic to organic sulfur in Springfield No. 5 coal (Source: http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_pyrstoorgsratio.pdf; IGS.)
Figure 2.5. Ratio of pyritic to organic sulfur in the Herrin No. 6 coal (Source: http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_pyrstoorgsratio.pdf).
(iv) **Bacterial Action:** The role of bacteria in accelerating the pyritic oxidation has been very well researched. Singer and Stumm (1970) put emphasis on the role *Thiobacillus ferrooxidans* play in the catalysis of the step where $\text{Fe}^{2+}$ iron is oxidized to $\text{Fe}^{3+}$ in acidic environment. Nicholson (1994) discovered that the pyritic oxidation rates are increased by 10-100 times due to presence of the above-mentioned bacteria species. The contributions of species such as *Leptospirillum ferrooxidans*, *Thiobacillus thiooxidans* to acid and sulfate generation process have been well documented. Bigham and Nordstrom (2000) have postulated that the presence of a variety of bacteria species enhances the pyrite oxidation more than any single bacteria species. This is understandable as 95% of bacteria species that aid the acidification process are not *Thiobacillus ferrooxidans* (Morin and Hutt, 2001).

Two mechanisms have been proposed for the bacterial action during the pyrite oxidation process (Evangelou, 1995). The first mechanism requires direct physical contact between the bacteria and the pyrite mineral surface. The second mechanism is indirect and works by catalyzing the rate of reaction of the $\text{Fe}^{2+}$ to $\text{Fe}^{3+}$ conversions, which in turn further oxidizes the pyrites.

(v) **Temperature:** Higher temperature increases the rate of the pyrite oxidation reaction and hence, leads to larger acid and sulfate generation (Nicholson, 1994). Temperature, when in the optimum range for activities of bacteria, may aid the entire process.

(vi) **Physical Characteristics of Coal Stockpiles, and Spoil and Coal Refuse Facilities:** Physical attributes of the pyrite and sulfate-bearing materials extracted and placed at the mine site will impact the mobilization of sulfate. This includes the material’s particle size distribution, porosity, air/water permeability, moisture content and spatial distribution of pyrite and sulfate-bearing material as determined by the mining, processing and disposal practices. These physical parameters control the progress of acidification. In the same refuse pile, these parameters vary with time, with the consolidation, weathering, segregation/re-arrangement and length of exposure of waste particles in the disposal area.

2.7 **Gaps in Current Knowledge Base**

There are several aspects of sulfate discharge and minimization that have not been fully studied. At present, there is no reliable technique that correctly predicts the incubation period between disposal of refuse in the disposal areas and the onset of sulfate-rich acidic discharges. Refuse piles are constructed with guidelines on stability, grade, and compaction. However, there are some geotechnical characteristics of both coarse (CCPW) and fine refuse (FCPW or slurry), such as compaction behavior (specifically for slurry), permeability etc. in the field are limited. Dewatering of fine refuse continues to be a major issue with coal mine operators, as it requires large surface footprints for slurry ponds. To the best of the authors’ knowledge, there has been no attempt on an industrial scale to pump dewatered slurry from the coal processing plant to the disposal areas. Another
important aspect to preventing sulfate generation is contemporaneous reclamation, which is currently implemented as required by regulation. However, it may be possible to reduce sulfate generation in problem areas by prioritizing the timing and focus of reclamation.
3.1 Introduction

It is well-established that presence of chlorine in coal can lead to chloride discharges and possible environmental issues if the chlorine content exceeds 0.25% - 0.3% of the coal (Raask, 1985; Gluskoter, 1967; McCormick and FitzPatrick, 1991). In few specific coal seams and mines in Illinois, the chlorine content reaches values in the range 0.8–1.0 %. Such high contents may have significant environmental implications (Gluskoter and Rees, 1964; Chou, 1991; Bragg et al., 1991). The release of chlorine as a gas requires a higher temperature than is typically encountered in the mining and processing environments. Early studies indicated that chlorine in coal is present in three major forms; 1) the dissolved anion chloride ions present in moisture of coal matrix, 2) chlorine present in the form of inorganic crystalline compounds, and 3) chlorine present as organo-chlorine compounds (Hodges and others, 1983). More recent observations indicate that chloride adsorbed onto organic molecule and dissolved in coal moisture within micropores are the dominant sources of chlorine in Illinois coal (Chou, 1991). If so, this allows ready liberation of chlorides into mine drainage. As soon as the coal is fragmented, as in extraction or processing, chlorides can be released with the amount directly related to the amount of fragmentation and leaching (McCormick and FitzPatrick, 1991). Most of the chlorine found in U.S. coals (about 65%) is water soluble (Huggins and Huffman, 1995; Gluskoter and Rees, 1964). Some studies indicate that saline sub-bituminous B-C coals have almost all the chlorine in water-soluble form. In general, these studies observed that the yield of water-soluble chlorine decreases as the rank of coal increases.

Wet fine grinding is a process, similar to fine coal cleaning for sulfur reduction that can be used to de-chlorinate high-chlorine coal for improvements in combustion or gasification performance (McCormick and FitzPatrick, 1991; DePriest and others, 1991). This will, however, mobilize the chloride ion in the process (McCormick and FitzPatrick, 1991). Conventional coal processing will similarly also liberate chlorine. Coal is also fragmented in the mining process, especially in underground mining where production machinery, continuous miners, longwall shearers, and conveyor belt feeder/breakers, reduce the coal to relatively small particle sizes. Studies also indicate that there is an inverse relationship between ash yield of a coal, both on total coal- and ash-basis, and chlorine content; an indicator that chlorine is linked to the organic fraction (Bragg and others, 1991; Chou, 1991). To date, conclusive studies have not been performed on the distribution of chlorine within a coal bed. One recent study indicates that in the high-volatile bituminous Springfield No. 5 Coal seam, the highest chlorine content was observed near the roof, pointing towards a post-sedimentation enrichment (Mastalerz and others, 2004).
3.2 Chlorine in Illinois Coals

Chlorine is an enriched element in Illinois Basin coals. The mean chlorine concentration in Illinois Basin coals is 800 mg/L, which is 5 to 6 times higher than the Clarke value (World average chlorine content) of 130 mg/L (Gluskoter et al., 1977). In the 1970’s, Gluskoter et al. (1977) analyzed 172 coal samples across the U.S. for trace element concentration. Of these 114 samples were from coal seams of the Illinois Basin. Both raw and washed coals were included in these samples. Chlorine concentration in coals tends to be highest in coals from higher rank coals of the Appalachian Basin (Eastern U.S.), lowest in the lower rank Western U.S. coals and intermediate in bituminous coals from Illinois Basin (Figure 3.1).

Gluskoter and Rees (1964) believed that most of the chlorine in Illinois coals occurs as inorganic chlorides (water soluble), primarily as sodium chloride. Both total (chlorine) and water soluble (chloride) concentrations are listed in Table 3.1. As observed from the table, a significant portion of total chlorine present in Illinois coal is water soluble. All samples collected were face channel samples. The average chlorine concentrations for each county are presented in Figure 3.2. Nine Illinois counties had average chlorine concentrations higher than 0.1 percent.

Figure 3.1. Chlorine (wt. %) in U.S. coal (Source: Gluskoter et al, 1977).

Figure 3.2. Average chlorine concentrations (wt. %) in Illinois coal by county.
Table 3.1. Total and Water-soluble Chlorine of Illinois Coal

<table>
<thead>
<tr>
<th>County</th>
<th>Coal No.</th>
<th>Total Chlorine (% dry)</th>
<th>Water Soluble Chlorine (% dry)</th>
<th>County</th>
<th>Coal No.</th>
<th>Total Chlorine (% dry)</th>
<th>Water Soluble Chlorine (% dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adams</td>
<td>2</td>
<td>0.04</td>
<td>0</td>
<td>Madison</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Adams</td>
<td>2</td>
<td>0.03</td>
<td>0.02</td>
<td>Marion</td>
<td>6</td>
<td>0.47</td>
<td>0.32</td>
</tr>
<tr>
<td>Brown</td>
<td>2</td>
<td>0.04</td>
<td>0.01</td>
<td>Marion</td>
<td>6</td>
<td>0.38</td>
<td>0.21</td>
</tr>
<tr>
<td>Brown</td>
<td>2</td>
<td>0.05</td>
<td>0.02</td>
<td>Mercer</td>
<td>6</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Bureau</td>
<td>6</td>
<td>0.02</td>
<td>0.02</td>
<td>Montgomery</td>
<td>6</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td>Bureau</td>
<td>6</td>
<td>0.02</td>
<td>0.01</td>
<td>Montgomery</td>
<td>6</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>Bureau</td>
<td>6</td>
<td>0.02</td>
<td>0.02</td>
<td>Montgomery</td>
<td>6</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.22</td>
<td>0.19</td>
<td>Montgomery</td>
<td>6</td>
<td>0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.24</td>
<td>0.23</td>
<td>Peoria</td>
<td>2</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.26</td>
<td>0.2</td>
<td>Peoria</td>
<td>2</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.62</td>
<td>0.5</td>
<td>Perry</td>
<td>6</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.65</td>
<td>0.48</td>
<td>Perry</td>
<td>6</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Christian</td>
<td>6</td>
<td>0.61</td>
<td>0.45</td>
<td>Randolph</td>
<td>6</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Douglas</td>
<td>6</td>
<td>0.07</td>
<td>0.03</td>
<td>Randolph</td>
<td>6</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Douglas</td>
<td>6</td>
<td>0.07</td>
<td>0.02</td>
<td>Randolph</td>
<td>6</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.22</td>
<td>0.02</td>
<td>St. Clair</td>
<td>6</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.25</td>
<td>0.06</td>
<td>St. Clair</td>
<td>6</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.27</td>
<td>0.07</td>
<td>St. Clair</td>
<td>6</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.41</td>
<td>0.02</td>
<td>St. Clair</td>
<td>6</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Franklin</td>
<td>5</td>
<td>0.20</td>
<td>0.03</td>
<td>St. Clair</td>
<td>6</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.20</td>
<td>0.03</td>
<td>Saline</td>
<td>4</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.21</td>
<td>0.09</td>
<td>Saline</td>
<td>4</td>
<td>0.22</td>
<td>0.01</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.23</td>
<td>0.11</td>
<td>Saline</td>
<td>5</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.21</td>
<td>0.12</td>
<td>Saline</td>
<td>5</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.26</td>
<td>0.11</td>
<td>Saline</td>
<td>5</td>
<td>0.16</td>
<td>0.01</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.04</td>
<td>0.19</td>
<td>Saline</td>
<td>5</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.39</td>
<td>0.13</td>
<td>Sangamon</td>
<td>5</td>
<td>0.19</td>
<td>0.16</td>
</tr>
<tr>
<td>Franklin</td>
<td>6</td>
<td>0.41</td>
<td>0.14</td>
<td>Sangamon</td>
<td>5</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>Fulton</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>Sangamon</td>
<td>5</td>
<td>0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Fulton</td>
<td>5</td>
<td>0.01</td>
<td>0</td>
<td>Schuyler</td>
<td>5</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Fulton</td>
<td>5</td>
<td>0.01</td>
<td>0</td>
<td>Schuyler</td>
<td>5</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Fulton</td>
<td>5</td>
<td>0.01</td>
<td>0.01</td>
<td>Stark</td>
<td>6</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Fulton</td>
<td>2</td>
<td>0.04</td>
<td>0.01</td>
<td>Stark</td>
<td>6</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.51</td>
<td>0.28</td>
<td>Vermilion</td>
<td>7</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.45</td>
<td>0.19</td>
<td>Vermilion</td>
<td>6</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.50</td>
<td>0.36</td>
<td>Vermilion</td>
<td>6</td>
<td>0.23</td>
<td>0.18</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.36</td>
<td>0.23</td>
<td>Vermilion</td>
<td>6</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.27</td>
<td>0.16</td>
<td>Vermilion</td>
<td>7</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.27</td>
<td>0.12</td>
<td>Vermilion</td>
<td>7</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.38</td>
<td>0.29</td>
<td>Vermilion</td>
<td>7</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.33</td>
<td>0.26</td>
<td>Vermilion</td>
<td>7</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.04</td>
<td>0.04</td>
<td>Vermilion</td>
<td>7</td>
<td>0.16</td>
<td>0.1</td>
</tr>
<tr>
<td>Jefferson</td>
<td>2</td>
<td>0.04</td>
<td>0.04</td>
<td>Williamson</td>
<td>6</td>
<td>0.28</td>
<td>0.1</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.06</td>
<td>0.01</td>
<td>Williamson</td>
<td>6</td>
<td>0.25</td>
<td>0.09</td>
</tr>
<tr>
<td>Jefferson</td>
<td>5</td>
<td>0.14</td>
<td>0.01</td>
<td>Williamson</td>
<td>6</td>
<td>0.25</td>
<td>0.08</td>
</tr>
<tr>
<td>Jefferson</td>
<td>5</td>
<td>0.12</td>
<td>0.01</td>
<td>Williamson</td>
<td>6</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.02</td>
<td>0.02</td>
<td>Williamson</td>
<td>6</td>
<td>0.19</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.03</td>
<td>0.02</td>
<td>Williamson</td>
<td>6</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.02</td>
<td>0.02</td>
<td>Williamson</td>
<td>6</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Jefferson</td>
<td>6</td>
<td>0.02</td>
<td>0.01</td>
<td>Williamson</td>
<td>6</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>0.13</td>
<td>0.04</td>
<td>Williamson</td>
<td>6</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>0.11</td>
<td>0.04</td>
<td>Williamson</td>
<td>5</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>0.09</td>
<td>0.04</td>
<td>Williamson</td>
<td>5</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>0.09</td>
<td>0.06</td>
<td>Williamson</td>
<td>6</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

22
<table>
<thead>
<tr>
<th></th>
<th>6</th>
<th>0.08</th>
<th>0.08</th>
<th></th>
<th>6</th>
<th>0.05</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>0.08</td>
<td>0.06</td>
<td>Williamson</td>
<td>6</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.07</td>
<td>0.03</td>
<td>Williamson</td>
<td>6</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.06</td>
<td>0.01</td>
<td>Williamson</td>
<td>6</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.12</td>
<td>0.1</td>
<td>Williamson</td>
<td>6</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.13</td>
<td>0.09</td>
<td>Williamson</td>
<td>6</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.06</td>
<td>0.02</td>
<td>Williamson</td>
<td>6</td>
<td>0.18</td>
<td>0.05</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>0.07</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Gluskoter and Rees, 1964

In the Illinois Coal basin, an increase in chlorine content is observed with depth of the carboniferous strata (Gluskoter and Rees, 1964; Chou, 1991; Figures 3.3 and 3.4). Chou (1991) found that for Illinois surface mines the chlorine content in the coal was rarely higher than 0.1 %, whereas for underground mines [deeper than 50 m. (164 ft.) depth] the chlorine content was higher, ranging from 0.1 – 0.5%. Mapping of chlorine content in Herrin seam of Illinois suggests that chlorine content follows the synclinal bed structure, increasing from its uplifted peripheral zones to its submerged central locations (Figure 3.5; Bragg et al., 1991). It is important to note that future mining in Illinois will trend toward a greater dependence on underground mining and toward these greater depths.

One of the reasons for wide variance in the percent of total chlorine extractable in water is the contribution of organically-bound chlorine (Gluskoter and Rees, 1964). The other is that it was believed that some of the chlorides were in the coal capillaries or micropores. Both Gluskoter and Rees (1964) and Bettelheim et al. (1982) found that finer coal particles can release more chloride upon leaching. Therefore, coal that is finely ground in processing (<200 μm) will be more prone to produce problematic chloride discharges. The amount of the chloride that can be leached out of coal samples also increases with time. However, Bettelheim et al. (1982) in a study of British coal (British coal can also exhibit a high chlorine content; also see Caswell et al. 1984) observed that for some coals the rate of release with time was constant, whereas others released a large amount of chloride initially followed by release at a lower rate. The latter was attributed to a condition where there are multiple chloride sources: Variations in leaching characteristics was also attributed to the maceral type and structure of the coal (Bettelheim et al., 1982; Chou, 1991). Chou (1991) found that the chlorine content is elevated in the vitrinite lithotype bands of an Illinois basin coal bed, decreasing sequentially through bright banded, sub-bright banded, impure coal (16.3 – 44.2% ash) and roof shale (47 – 66.7% ash) with a corresponding increase in ash content.

In contrast sodium is positively correlated in this coal bed with ash content. Chou (1991) suggests that there are two principle sources of chlorine: 1) Chlorine as dissolved chloride anion (Cl\(^-\)) as well as the anion Br\(^-\) ion along with cation Na\(^+\) in pore water (Bragg and others, 1991), and 2) chloride ions adsorbed onto coal organic molecules. In contrast, sodium is adsorbed onto clay particles and as such is associated with the ash. The ability to remove chlorine from coal by fine grinding, soaking (extended cold-water leaching), and more aggressive leaching (hot water and dimethyl sulfoxide-DMSO) is an indicator that the Cl\(^-\) ions are adsorbed and not bound to the organic structure (Chou, 1991).
Comparing the depth of the coal with the iso-chlore (chlorine isopach) map, the aerial distribution of chlorine in Herrin coal (Figure 3.5) exhibits a strong positive relationship between chlorine content and coal depth. Salinity in ground water typically increases with depth. In their study of a large federal coal analysis database, Bragg et al (1991) observed a strong positive correlation ($r^2 = 0.86$) with bromine (ionic form = bromide, Br$^-$) in Interior Basin coal, and its presence along with chlorine are an indicator of a marine origin. Bromine occurs in seawater as the sodium salt, but in much smaller quantities than chloride. The correlation between depth of coal and chlorine content in the Illinois Basin coal is indicative of an equilibrium condition with the chlorine content in the coal and the chlorine (as chloride) in the ground water (Chou, 1991). Using a pre-1964 data compilation, Gluskoter and Rees (1964) developed a similar finding based on almost 100 chemical analyses of the Herrin (No.6) coal samples. For coals buried between 0-650 feet under the earth surface, chlorine percentage is about 0.1% while for coals between 650-1000 feet under the surface, chlorine percentage ranges from 0.2 to 0.5%. If the mining depth is over 1000 feet, chlorine concentration in the coals is as high as 0.6%. The chloride content in Illinois coals overall has a weak positive ($r^2 = 0.48$) correlation with sodium (Na$^{2+}$) concentration (Gluskoter and others, 1977, p. 41-43). Chou found a stronger relationship with sodium in two Illinois coal beds; the Herrin ($r^2 = 0.83$) and the Springfield ($r^2 = 0.73$). According to Gluskoter (1965) the correlation of chlorine and depth to the coal bed is the result of an increase in salinity of ground water with greater depth. However, there does not appear to be a simple equilibrium condition with sodium chloride. Chou found that the Na/Cl ratio is very variable in Illinois coal.

Majority of the chlorides present in coal particles are liberated during the coal cleaning processes in the preparation plant. Mechanical processes such as grinding, floatation and centrifuges impart enough mechanical energy on the coal particles to release the adsorbed chlorines species into solution. Meanwhile, ionic chlorides also go into solution. Remaining chlorides present in coal refuse get released in disposal areas. Both coarse and fine refuse materials are leached from the time they are deposited in the disposal areas to the time reclamation process is complete. Recirculation water circuits bring the chlorides that have been leached out to the coal preparation plant and lead to a build-up in chloride concentration. In case of heavy rainfall events, most of the excess run-off has to be discharged outside the permit boundary. In such instances, the chlorides present in the run-off report to external water bodies.
Figure 3.3. Chlorine content of the Springfield coal in Illinois (Source: ISGS, [http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_cl.pdf](http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/springfield_cl.pdf)).
Figure 3.4. Chlorine content of the Herrin coal in Illinois (Source: ISGS, http://www.isgs.uiuc.edu/coalsec/coal/trace_element_maps/herrin_cl.pdf).
3.3 Gaps in Current Knowledge Base

The risk assessment of high chloride discharges, as they relate to chlorine occurrences in the coal, roof or floor, has not been studied. Very little is also known on the chloride leaching processes as they relate to coal preparation plant processes and in the refuse disposal practices. Currently, no good management practice (GMP) other than water management and application of mixing zones are available to mitigate high chloride discharges such as those, which may be encountered in underground-mining in Illinois. Water treatment technologies for removal of chlorides are generally considered cost prohibitive.
CHAPTER 4
PERMIT APPLICATION DOCUMENTS REVIEW

4.1 Introduction

Environmental permits for surface coal mines, coal processing and refuse disposal operations and the surface effects of underground coal mines are issued by Illinois Department of Natural Resources (IDNR), the authorized state regulatory authority under the Surface Mine Control and Reclamation Act of 1977 (SMCRA, 30 CFR 731). Water discharge permits are issued by the Illinois Environmental Protection Agency (IEPA) under the authority of the Clean Water Act. Other environmental- and safety-related approvals are required from state and federal agencies for mining impacts on, for example, wetlands, groundwater, and worker safety.

Mine permit application process for Illinois coal mining operations documents the mining and reclamation practices. These documents contain baseline information about the mine, coal seam, production rates, geologic maps, engineering design, operations plans, revisions, and communications between operators and regulatory agencies. Some of the information contained in the mine permit applications can be used to gain insights into potential sulfate and chlorides discharge issues. Hence, a study was undertaken to review mine permit applications documents to gain an understanding of coal refuse management practices. The specific objectives of this task were:

1. Identification of pre-mining, operational and reclamation factors that may influence discharge levels.
2. Identify any inter-relationships that may exist among different factors that ultimately contribute to sulfate and chloride discharges.
3. Assess various current practices from sulfate and chloride discharges points of view.
4. Identify any information that does not find mention in the permit application process, but may be of significance.

4.2 Task Approach

Mine permit application documents were obtained from Illinois Department of Natural Resources (IDNR). Permit documents for 19 active surface and underground coal mines were reviewed. The review included:
1. Application documents.
2. Maps of mining operations, surface structures, lithology, etc.
3. Aerial photographs.
4. Communication between operators and regulatory agencies.
5. Specific study reports provided by consultants and researchers.
6. Miscellaneous supporting technical documents and reports.
7. Water quality data of samples obtained from the NPDES locations were also reviewed and analyzed.
4.3 Variables Studied

The variables that were considered most significant are discussed below.
(i) Geo-mining conditions.
(ii) Hydro-geologic information.
(iii) Hydro-geologic impact statements made by operators.
(iv) Refuse characteristics.
(v) Operational and reclamation practices used.
(vi) Sulfate and chloride water quality data.
(vii) Miscellaneous information.

4.4 Geo-mining Factors

- Location: Sulfur and chlorine content in Illinois coal strata is both location- and seam-specific. The geologic structure of the Illinois coal deposits is in the form of a saucer and as a result coal is mined at different depths. Due to the marine influence during the formation of the coal-bearing strata the inherent amounts of pyritic sulfur and chlorine in Illinois deposits are typically high. Due to the increasing amount of dissolved solids in the groundwater of the Illinois Coal basin with depth of burial, the amount of chlorine has been found to have positive correlation with depth of coal. Thus the location of a coal mine in Illinois has influence on the sulfate and chlorides that may eventually appear in the surface discharge water.

- Coal seam: There are two major mineable coal seams in Illinois, the Herrin (#6) seam and Springfield (#5) seam of the Carbondale Formation. Springfield seam is the deeper of the two and it has larger average pyritic sulfur and chlorine contents. The Springfield seam also has a larger range for pyritic sulfur and chlorine values. One lower Carbondale Formation coal zone, the Davis and Decoven coal interval, is seldom mined today due to high acid-forming potential of associated strata (in particular the Palzo Sandstone Member).

- Coal characteristics: The forms of sulfur and chlorine occurrence within the coal will affect the ultimate discharge levels of sulfate and chlorides. Most of the adsorbed chlorine present in coal is rapidly released in the coal preparation plant. The sulfur minerals in the coal are removed during coal cleaning and they weather at a slower rate in the refuse disposal area increasing surface area and oxidation potential. The mineral pyrite in refuse chemically decomposes slowly and results in sulfate discharge.

- Roof and floor characteristics: During mining of coal, some of the immediate roof and floor strata are also mined. Roof strata such as black carbonaceous shale found in Illinois coal basin are generally associated with high pyritic sulfur content. On the other hand roof strata such as limestone generally contain very small amount of pyritic sulfur. Underclay or claystone is the most common floor stratum in Illinois coal mines and is usually low in sulfur and chlorine. Excavated
roof shale, coal impurities and partings (rock bands within coal seam), and floor material are separated during the coal preparation process and form the run-of-mine coal refuse or coal processing waste. Since refuse characteristics influence surface discharge levels, the original sulfur and chlorine characteristics of both roof and floor and rock bands in coal are of significance. The current requirements for geochemical boring data are sufficient to characterize refuse in most cases. However, site-specific conditions may warrant that additional geochemical data analyses be performed. This could be achieved by geochemical analyses of crushed rock fragments from testing of roof and floor samples for geotechnical studies. This would allow evaluation of the spatial relationships of sulfur and chlorine content in these rocks. The advantages of an understanding of spatial relationships of sulfur and chlorine content to stratigraphic units will become apparent in a GMP discussion of selective mining in Chapter 8.

- Mining method: Whether coal is mined through surface or underground mining methods has large impact on ultimate sulfate discharge levels. Surface mines usually dispose coarse coal processing waste (CCPW) in the open pit from which the coal has been removed. Fine coal processing waste (FCPW) or slurry is pumped into last open cuts that are typically narrow and long in Illinois. Out-of-seam dilution (OSD) is minimal in surface mines since operators carefully scrape the surface of coal before loading it out. Unless the CCPW and FCPW are placed improperly high in the backfill, most of the AMD and sulfate generation in surface mines are related to oxidation of overburden rather than processing waste. Since slurry disposal areas are long and narrow, deltas of coarse, pyrite-rich slurry exposed to weathering and oxidation in the slurry discharge area are limited. Concurrent reclamation requirements in surface mining minimize oxidation and weathering issues from the spoil materials. Placement of CCPW and FCPW in the bottom of the pit below the water table limits sulfate discharge from coal refuse placed in surface mines. Thus sulfate discharge problems from surface mines should be minimal.

For typical Illinois underground-mines that access the coal from shafts and slopes extending from level ground, both CCPW and FCPW are typically disposed above ground level into large structures that are more readily exposed to oxidation and weathering. Slurry is disposed into large settling ponds surrounded by embankments constructed of CCPW. Normally FCPW is discharged from a single discharge point that is either fixed or moved on an infrequent basis. The inner and outer slopes of CCPW embankments may not be completely compacted and, as a result, are subject to weathering and oxidation. For Illinois underground mines the out-of-seam dilution is typically high, ranging from 30-50%. Most of the AMD and sulfate generation is related to oxidation of coal processing waste where the pyrite is contained in the coal and out-of-seam dilution rock. There is very little overburden material in a typical Illinois underground mine that can contribute to the sulfate and chloride discharges. However, groundwater pumped from the underground mines and or/dewatering boreholes can contribute to the majority of the chloride discharge and in some cases sulfate discharge.
Excavated surface impoundments are typically used to dispose FCPW in the absence of co-placement of mixed coarse and fine refuse facility. Additional impoundments are built at mine sites to trap sediments from run-off water and/or hold water for processing facility use or as a fresh water source for the mine, coal processing make-up water and dilution of the off-site discharge water. Some of these ponds collect the affected run-off through series of drains, ditches etc. that form the mine-site surface drainage network.

- **Subsidence**: In case of underground coal mines, subsidence fractures may occur in the overburden due to post-mining ground movements. Subsidence fractures may temporarily open up water flow channels in the overburden strata and increase leaching of sulfates and chlorides underground. It is recognized that the impact of mine water inflow due to subsidence on sulfate and chloride levels in the underground discharge is poorly understood at this time.

- **Proximity of old coal mine workings and oil and gas wells**: A number of operating Illinois coal mines are in close proximity to old surface and underground mine workings. As a result the sulfate and chloride levels in the discharge can be affected by hydraulic connections with these operations. Interaction with nearby historic oil and gas production activity such abandoned brine injection wells could potentially increase the chloride discharge levels if an abandoned well is intercepted by mining and conditions favor confined, brine charged aquifer to discharge into the mine workings. This is a condition that should be investigated. The presence of historic coal, oil and gas or other industrial activities such as brine production and waste fluid injection, must be considered in any effort to control sulfate and chloride discharges at coal mines in the region.

### 4.5 Hydro-geologic Factors

Hydro-geology of a coal mine site controls leaching and run-off processes as well as discharges of groundwater during the mining processes.

- **Strata characteristics**: The pre- and post-mining hydraulic parameters (porosity, hydraulic conductivity, transmissivity, and specific yield) and geochemistry of the overburden strata will impact the quantity and quality of water before and after mining. These factors also control the run-off water quality in surface and underground mines. For example, due to fragmentation of overburden strata during surface coal mining, the hydraulic conductivity of the strata (spoil) will be increased resulting in increased recharge and groundwater base flow to ephemeral and perennial streams and deep-water impoundments.

- **Water flow conditions**: Water flow conditions in underground coal mines are dictated by presence of water-bearing strata and, in the Illinois Basin, fractures that allow water to be transported. Similarly, surface water flow is controlled by
watershed topography, the physical characteristics of the surficial materials, and interactions with groundwater flow.

- Baseline water quality: Baseline water quality and quantity information establishes pre-mining conditions of water resources. Baseline conditions establish the usefulness of these resources and serve as a gauge for evaluating the impact of coal mining. Most permits reviewed contained considerable baseline groundwater and surface water information, which details up-gradient and down-gradient sulfate and chloride levels in the proposed mining area, as required by current regulations. Unfortunately, baseline surface water quality data was not included in all reviewed permit applications. This may be due to the closed-loop water handling system employed by many Illinois mining operations and the assumption that no water will ever leave the site. This limits the permit reviewers understanding of baseline conditions of the receiving water bodies and the ability of these water bodies to tolerate an increase in sulfate and chloride levels due to coal mining and processing activities. A reviewer requires this knowledge in the preparation of SMCRA required “Cumulative Hydrologic Impact Assessment (CHIA)” and the surface water material damage criteria.

4.6 Refuse Characteristics

Refuse or spoils generated during either underground or surface coal mining form the sources of sulfate and chloride discharges. Hence, their characteristics have significant effect on the final quality of discharged water. The refuse characteristics of interest include geotechnical and geochemical.

The construction of refuse/spoil piles, and sediment ponds should always be based on sound geotechnical principles. The size, shape and construction methods/equipment for refuse piles and impoundments are guided primarily on safety against failure of such a structure and are subject to MSHA requirements. During and after construction of the above structures, geotechnical characteristics control the geochemical processes such as oxidation and weathering, availability of water, leaching and surface run-off. These are briefly discussed below.

- Particle size: Particle size distribution of refuse affects the size of refuse disposal structure. Particle sizes and their distribution control the compaction characteristics, including maximum compaction density that may be achieved during the disposal, and selection of appropriate compaction equipment. This in turn affects permeability of the refuse mass to any leaching fluid.

- Permeability: Permeability of the refuse controls the water table, draw-down curve, migration of contaminants out of the refuse piles, and oxidation rates. The embankment slopes that are generally not well compacted have much higher air and water permeability and affect acid mine drainage (AMD) and sulfate discharges. These discharges (rich in ferric iron) typically run into FCPW or
slurry disposal areas can accelerate slurry oxidation and acidification locally or areally.

- Geochemical characteristics of refuse/spoil: Different types of refuse generated from a processing plant have different geochemical characteristics and the ratios in which they are generated affect rate of acidification and ultimate sulfate discharge levels. Physical characteristics such as size and shape of particles also affect geochemical processes. Similarly, overburden spoils generated during a surface mine operation may have different characteristics than coal refuse.

- Oxidation and weathering and neutralization potential of refuse: Most of the refuse materials evaluated during this study had some base alkalinity associated with them. However, this potential is used in neutralizing acidity generated by pyrite weathering during the initial oxidation process. Therefore, fresh refuse which still contains most of the inherent neutralization potential will generate less acidity than weathered refuse and result in a favorable discharge pH (6 - 9). However, at this pH the pyrite oxidizing bacteria are still active and some sulfate generation will continue. At most mine sites pyrite oxidation plays a central role in generation of sulfate. Over time the weathering process will degrade the refuse, increase surface area for pyrite weathering and increase sulfate production. Upon exhaustion of the pyrite and weathering products (acid salts) the sulfate liberation will finally decline.

4.7 Hydro-geologic Impact Statement

Hydro-geologic impact statement included in the permit application elaborates potential short-term and long-term impacts of mining, processing and reclamation operations. However, the majority of hydro-geologic statements of permits reviewed during this study could have addressed the issues of long-term sulfate and chloride discharges more thoroughly.

4.8 Current Waste Management Practices in Underground Coal Mines

Underground coal mine operations in Illinois use combinations of CCPW embankments, sediment ponds and surface drainage network to minimize adverse environmental effects of mining, processing, waste management and reclamation activity. Current CCPW (refuse) structures are typically pyramid shaped, stepped structures. Majority of active mines dispose CCPW and FCPW in separate structures. Some operators have their CCPW structures built around FCPW structures at the center. Some operators co-dispose their FCPW and CCPW by mixing them together. Some CCPW structures are constructed from CCPW mixed with clay or fly ash to improve their compaction and reduce their hydraulic conductivity. After the CCPW and FCPW structures are completed, they are capped by top-soil or sub-soil that have been removed and stored from within or outside the mine permits area. Alkaline amendments are added as appropriate in the upper portions of graded CCPW before putting the soil cover. The soil cover cap is then vegetated.
4.9 Current Spoil Management Practices in Surface Coal Mines

Active surface coal mine operations in Illinois adopt approaches similar to underground mines with regard to the management of overburden spoils. The surface mines also use a combination of spoil pits, surface drainage network and sediment ponds to minimize potential of run-off water contamination. Coal processing waste is typically deposited at the bottom of the pit after removal of coal. This is done prior to dumping of overburden spoils. In Illinois overburden in the past was typically excavated using shovel, dragline, or bucket-wheel excavator and placed behind in the strip opposite to the highwall from where coal had been extracted (strip mining). The operating pit extended laterally a distance of 5,000 ft to 10,000 ft. In recent years the prime movers of overburden are large tractor-bulldozers and hydraulic excavator-truck combination since operations are smaller mining at relatively shallow depth. Subsequently, these spoils are graded and topsoil and subsoil are replaced to form the rooting medium for the establishment of vegetation. Sedimentation control impoundments are the principle means to collect sediments and improve water quality prior to offsite discharge. Whenever these impoundments are no longer required to control runoff water, they are also graded, covered with topsoil and subsoil, and vegetated.

4.10 Operational Factors

Some of the mining practices in a surface coal mine that affect the surface run-off water quality are given below.

- Relative geographic location of surface facilities such as coal processing plant, coal storage yard, refuse piles, sediment ponds, drainage system affect the water quality at the final discharge locations.
- Haulage, stacking and compaction methods for refuse disposal affect the weathering process of the refuse and have bearing on the final surface discharge water quality.
- Sediment ponds receiving runoff from coal stockpiles and non-reclaimed coal waste areas contain some sulfate and chlorine-bearing coal and coal refuse particles. During dry periods the sediment ponds may be exposed to air and desiccation effects (acidic sulfate salt formation). However, in Illinois this is generally not an issue because most sediment ponds do not dry to the point that the contained sediments are exposed to air.
- Normal and flood time drainage plan (i.e. ditches, berms and ponds) of the mine regulate the extent of dilution achieved inside the mine permit boundary before any run-off water is released outside.
- Design of water holding and fresh dilution water impoundments impacts the ability of the operation to dilute contaminants.

4.11 Reclamation Factors

During the reclamation process, several practices affect the surface discharge water quality. For example:
• Level of compaction achieved during construction of disposal structures and moisture content in the waste during the construction process governs the rate of leaching process and discharge of contaminants.
• Amendments such as agricultural lime, cement kiln dust and coal combustion byproducts modifies both the physical and geochemical properties of the fill and as a result affect both the stability of the structure and the chemistry of any leachate from the facility.
• Characteristics and thickness of final soil cover significantly affects the leaching and contaminant discharge process. Acidic- and sulfate-bearing discharges may be reduced where well-designed, engineered covers are emplaced. These include a compacted layer for limitation of infiltration into the acid-and sulfate-forming material overlain by a higher hydraulic conductivity layer for drainage (the capillary-break layer) and then a non-compacted rooting medium at least 2-foot thick.
• Any long-term erosion and subsequent exposure of waste in their respective impoundments may accelerate the oxidation process and discharge of contaminants.
• Contemporaneous reclamation has significant impact on the water quality. Wherever feasible the timely covering and revegetation of acid- and sulfate-forming materials will aid in reducing sulfate discharge.

4.12 Inter-relationships between Factors

There are several factors within the above-mentioned groups that may have interrelation with other factors and water quality. For example:
• Elevated chloride levels can affect sulfate level due to the ion pairing effect.
• Presence of CaCO₃ can affect sulfate level, but only under conditions of high pH, calcium and sulfate concentrations.
• Presence of CaCO₃ generally does not affect the chloride level.
• Compaction of waste affects its permeability and geotechnical properties.
• Subsidence or ground movement fractures may expose active mine workings to pre-existing mine workings and pollution sources.

4.13 Good Management Practices

During the mine permit applications review process, the project team identified several practices as good practices from sulfate and chloride discharges control point of view.
• Covering of weathered refuse with fresh refuse in a timely fashion to minimize acidifying the weathered and oxidizing waste. However, this practice was not extensively observed at the mines visited.
• Mixing alkaline waste materials such as cement kiln dust (CKD) or alkaline coal combustion byproducts (Type C fly ash or fluidized bed combustion ash) in bulk with CCPW prior to disposal to increase base neutralization potential and making it relatively impermeable to air and water. Obviously, this practice can only be
adopted if economic potential for management of such materials exists at the mine.

- Improved slope design with potential to eliminate some terraces and drainage channels on the inside and outside slopes of disposal structures that collect leachate and let runoff to infiltrate the structure. Such practices allow increased acidification and sulfate discharge from the refuse and also negatively impact structural stability. Improved slope design is possible today with innovative design software such as *Natural Regrade* by Carlson Software of Mayfield, Kentucky.
- Locating dilution lakes and sediment ponds below reclaimed areas to catch fresh water run-off.
- Moving slurry discharge points. However, the moving was not frequent enough and the discharge pipe was too far from the pond water surface at the mines visited.
- Application of slurry distribution manifold at a few mines.
- Application of co-disposal of CCPW and dewatered FCPW.

### 4.14 Inappropriate Management Practices

During mine visits, some management practices were observed that would have potential to increase the sulfate and chloride levels in the surface discharge water.

- Refuse was apparently exposed for long periods without covering it with fresh unoxidized waste or compaction.
- Constructing CCPW disposal structures in thicker lifts (one foot or greater) that would result in lower compaction levels and larger permeability to air and water.
- Non-compacted haul roads and safety berms may be an additional source for sulfate. Although the roadway surfaces are in some cases well compacted and resistant to weathering, some facilities are characterized by loose, deeply rutted haul roads. Typically, the safety berms and roadway out-slopes were non-compacted and were subject to weathering.
- Placement of coal refuse high in the backfill for extended periods of time at surface mine sites.
- Allowing deltas to develop in slurry ponds without ponded water that would allow oxidation and weathering of the FCPW sediments.
- Application of fixed slurry pipe discharge points.
- Minimal compaction of CCPW in some refuse disposal areas especially on and near out slopes and equipment safety berms.
- No apparent systematic discharge (blow-down) of high sulfate and chloride water within the coal washing circuit. The use of water with a relatively low sulfate and chloride in the coal preparation plant is needed to minimize excessive formation of readily-soluble desiccation salts (i.e. calcium chloride, calcium sulfate, and magnesium sulfate) on fresh coal waste and clean coal surfaces.
4.15 Permit Applications Information

Permit applications review helped establish the factors that influence sulfate and chloride levels discharged from Illinois coal mine operations. Although most current applications include sufficient information to accurately predict and characterize sulfate and chloride sources and discharges, certain site-specific attributes may warrant additional information. If sulfate and chloride discharges are expected to be problematic, this information has the potential to assist the operator in predicting and reducing these discharges.

Coal processing determines the quality of different waste fractions and their characteristics that directly impact sulfate and chloride discharges, material handling systems, and waste weathering and oxidation characteristics. There is limited information on the geochemical characteristics of the various processing waste fractions. If discharge concentrations from processing waste areas become problematic, this information can be used to adapt management techniques.

- Although some information may be present on water quantity, typically little information is available on water quality on the discharge from dewatering pumps in underground coal mines. In the event of high discharge concentrations, this information can be used to evaluate dilution water requirements.

- Some acid-base accounting (ABA) data is available, but this information is typically insufficient to spatially evaluate the ability of selective mining for sulfate and chloride control. If selective mining is implemented at an operation, additional ABA data can be obtained through the existing sampling required for geotechnical characterization (e.g. roof and floor stability).

- Geotechnical characteristics and placement conditions of CCPW such as particle size, compaction characteristics, and hydraulic conductivity are also not always included. Much of this information can be inferred through knowledge of the washing process and existing core analyses. Once mining is initiated, refuse compaction should be periodically measured using nuclear gauge in compliance with the Mining Safety and Health Administration (MSHA) dam safety requirements that govern impoundments which are classified as “MSHA-sized.” The dam safety evaluation techniques and data reporting characteristics vary on a permit-to-permit basis and at the discretion of the MSHA regional office. The requirements for construction and monitoring of the structure are determined by evaluating the hazard rating of facility. Parts of the state including portions of southern Illinois possess an elevated seismic hazard which is considered in the overall structure hazard rating factor.
CHAPTER 5
WATER QUALITY DATA ANALYSIS FOR SULFATE AND CHLORIDE DISCHARGES

5.1 Introduction

As a requirement for a SMCRA permit every proposed Illinois coal mine is required to submit pre-mining water quality data to the Office of Mines and Minerals of the Illinois Department of Natural Resources. For surface water at least 6 months of baseline water quality data is needed for the receiving water bodies (typically both upstream and downstream). The parameters that are to be reported at the minimum include pH, total dissolved solids, total acidity, total alkalinity, hardness, sulfates, chlorides, total iron and total manganese. The coal mine operator must also state whether sulfates and chlorides will be increased in surface or groundwater due to the mining operations. Additional baseline information is required for groundwater present in water bearing strata both up-gradient and down-gradient of the proposed operation. Illinois surface water and groundwater (Section 620) regulations include requirements for the operator to conduct sampling and analysis for the inorganic parameters listed below [Section 620.410 (Class I Standards) and 620.450 (Alternate Groundwater Standards), concentrations of chemical constituents applicable to groundwater]:

Antimony  Copper  Silver
Arsenic    Cyanide  Sulfate
Barium     Fluoride  Thallium
Beryllium  Iron     Total Dissolved
Boron      Lead     Solids (TDS)
Cadmium    Manganese Zinc
Chloride   Mercury
Chromium   Nickel
Cobalt     Selenium

After mining and coal preparation begins, both the Clean Water Act’s National Pollutant Discharge Elimination System (NPDES) permit issued by the IEPA and the IDNR-OMM issued SMCRA permit require (as part of the surface water monitoring program) water sampling, analyses and reporting of all point source discharge locations (outfalls). Though the sampling method and frequency requirements may vary from permit to permit, typically quarterly samples analyses which include sulfate and chloride for both upstream and downstream stations are required. In addition all outfalls that are discharging during that period are typically sampled nine (9) times a quarter from which the monthly average and daily maximum values are derived. Historically, sulfate effluent limitations in the discharge have been less than or equal to a daily maximum of 3,500 mg/L. However, the coal mine operator could be permitted to discharge more than 3,500 mg/L, if it could be shown by actual stream studies that the sulfate discharge was not causing any adverse environmental effects.
A coal mine operator may also be required to perform ground water monitoring for sulfates. The wells and springs that are monitored are located inside or within one-half (½) mile of the permit area. The operator also has to report whether there will be any discharges into underground mine workings or whether ground water is being pumped out of the mine. The operator is also required to identify all public water supply sources within 10 miles of the permit boundary and has to list the adverse effects on these water bodies due to the mining activities.

A typical coal mine complex (underground mine shafts, drift portals and slopes and their associated coal preparation facilities) operates a closed loop water system. However, in Illinois a typical underground coal mine and associated preparation plan complex will have net deficit of water during the course of a typical year. This is largely due to water lost during the mining process (dust suppression) and coal washing. Most water exits the facility as evaporation or surface moisture on the washed coal. To supplement their needs these operations add water from a fresh water impoundment or groundwater source. Periodic discharges (blow down) will occur typically from a single sedimentation control basin. Often this blow down occurs during a period of high precipitation, but the principal need for blow down is to purge water that becomes detrimental to equipment operation.

To supplement the perimeter sedimentation basins additional holding ponds are usually employed to collect runoff from the surface facility and pump discharges from mine workings. The water from these facilities is used in the operation (i.e. fire control and dust suppression systems) and coal handing and preparation facilities (coal washing and dust control, Figure 5.1). A large amount of water is also stored in slurry impoundments. During periods of intense, long-duration precipitation events these underground mine complexes may release water through the permitted outfall(s). Figure 5.2 shows a typical surface water management system. Here water from refuse disposal areas is routed through a network of ditches to one or more sediment impoundments. Any outflow from these impoundments serves as the mine discharge, in this case at Outfall 003. Although Illinois mine operators have applied a number of conventional management practices to control sulfate and chloride discharges, some of these facilities have difficulty in controlling the level of these pollutants.

This study has identified a significant relationship between the sulfate and chloride discharges levels and precipitation (rainfall and snow) events, which will dilute sulfate and chloride levels and lower the discharge concentrations. There is typically a time lag following a large precipitation event and resultant change in the discharge concentration of sulfate and chloride. Important factors that contribute to these changes are site-specific hydrology (i.e. the location of the sampling point in relation to the source of the pollutant), the geochemical environment at the time of precipitation (i.e. a preceding period of desiccation and sulfate and chloride salt formation). Another variable is the timing and quality of water measurement, sampling and analyses. However, the regulatory sampling program protocols are
designed to obtain an accurate range of concentrations that sufficiently characterize the discharges from a basin.

Figure 5.1. Typical water-management flow chart for an Illinois mine complex

Figure 5.2. Typical layout of refuse disposal area, sediment pond and NPDES discharge point.
5.2 Task Goal and Specific Objectives

The goal of this task was to evaluate historic sulfate and chloride data from Illinois mines to determine trends in the data, the magnitude of the problematic discharges and the correlation between mine operation factors, precipitation and the occurrence of elevated discharges. An attempt was made to categorize outfalls according to their historic maximum discharge of sulfates and chlorides. Subsequently, individual outfalls were analyzed for discernible trends in their sulfate and chloride discharge patterns, in conjunction with available precipitation data. The objective of this analysis was to assess the significance of precipitation and factors such as mine operation type, operational practices, and geochemistry of sulfate and chloride discharges.

5.3 Data Collection and Analyses

Sulfate and chloride leachate concentration data, analyzed in this study, were obtained from Illinois Department of Natural Resources (IDNR) that maintains an electronic database of such data. The data collected contained sulfate and chloride concentrations of NPDES discharges, sampled and analyzed by coal mine operators statewide at monthly intervals. As surface water discharges are directly related to precipitation events, it was imperative that any analyses of sulfate and chloride concentrations in the discharge water be performed in conjunction with the local precipitation trends. For this purpose, precipitation data for towns neighboring all the coal mine operations were obtained from National Climatic Data Center (NCDC). Monthly sulfate and chloride leachate concentrations were plotted against the local monthly precipitation data. The analyses period for each mine was from the time the first water quality monitoring was performed to the most recent monitoring data reported by the operator. The purpose of plotting sulfate and chloride water quality from a coal mine along with the local precipitation data on the same time scale was to analyze if precipitation is a predominant factor in deciding the discharge water sulfate and chloride concentration or do other factors offset the effect of precipitation.

5.4 Results and Discussion

Outfalls were categorized according to the frequency of maximum sulfate and chloride concentrations they have historically discharged. The results of the categorization of surface and underground mine outfalls for sulfate are presented in Figure 5.3. Ten (10) percent of underground coal mine outfalls had problematic discharges, with the highest value exceeding 2,500 mg/L. Surface mine outfalls were found to be lower than underground mines; no surface mines discharged water with sulfate concentrations of greater than 2,500 mg/L.
Similar data for chloride concentration are presented in Figures 5.4 and 5.5. Approximately 90% of underground mine outfalls had maximum discharge of chloride less than 1,600 mg/L (Figure 5.5). Only about 10% of the underground coal mines had chloride discharge of greater than 1,600 mg/L. No surface mine outfalls exhibited a high chloride discharge. The maximum chloride discharge for about 97% of surface mine outfalls were below 18.5 mg/L (Figure 5.5).
Two trends emerge from categorization of coal mine outfalls according to their historic maximum sulfate and chloride levels: 1) the majority (70%) of NPDES sulfate and chloride concentrations in the discharge water appear to have direct correlation with the precipitation data; and 2) sulfate and chloride data from the remaining NPDES points did not exhibit any noticeable correlation with precipitation data. Evaluation of these trends is presented below using examples from current Illinois mines.

(i) Effect of precipitation: A decrease in sulfate and chloride concentration could be typically expected under some conditions following a precipitation due to dilution. Similarly, rising sulfate and chloride concentration may be expected following a dry period. The data indicates periods where significant precipitation will trigger an abrupt increase in sulfate levels (Figure 5.6). This is due to the mobilization (flushing) of sulfate from calcium, magnesium and iron salts and chloride from sodium and potassium salts adhering to the particle surfaces in the coal stockpiles and refuse piles. However, this increase is relatively short lived and dilution allows for a rapid reduction in sulfate level of the discharge in about one or two months. There is also a small amount of lag following precipitation due to the time for the water to travel the flow path to the sampling point. The type of precipitation is also a factor as the impact of winter ice and snow is delayed until melting (Figures 5.6, 5.7, and 5.8). Trends in sulfate and chloride discharge from underground mine #3, underground mine #4 and surface mine #10 all show similar results, showing that there is a lag of about one month between variation in precipitation and corresponding change in sulfate concentration. This duration is variable, because of water quality sampling issues and whether there was a build-up of salts prior to the precipitation event. Because sampling is conducted at one month intervals (not dictated by precipitation),

![Figure 5.5. Chloride concentration distribution for discharges from Illinois surface mines.](image-url)
considerable variation in sulfate/chloride concentrations would be expected and does occur.

**Figure 5.6.** Sulfate concentration vs. precipitation for underground mine #3.

The relationship of sulfate concentration to precipitation is not as distinct for underground mine #3 (the chloride concentration for the same mine also did not exhibit any correlation). Factors such as geochemistry and operational practices of the mine site are likely to be factors in this discrepancy. For example, the site-specific hydrology of the site may dictate that the sulfate flushing process is longer than for mine #3. The two spikes in the sulfate levels for underground mine #3 show typical sulfate salt flushing events (Figure 5.6). Both of these spikes in the discharge sulfate concentration were observed during the 55th and 62nd months of data collection whereas heavy precipitation events occurred in the 35th and 40th month. Similar observations were made for the data presented for chlorides in underground mine #4 (Figure 5.7) and sulfates in underground mine #10 (Figure 5.8). One unknown variable is whether these coal mine stored high chloride or sulfate in mine site impoundments and intentionally released high concentration discharges as a blow-down event.
(ii) Effect of operational factors: Operational factors may also control the variations in sulfate and chloride discharge from the within the permit boundary of a coal mine. For example, reclamation of disposal sites or the availability of dilution water source can significantly reduce the sulfate and chloride concentrations. These operational activities will moderate the correlation between the precipitation data and sulfate/chloride concentrations in the NPDES discharge water. Overall sulfate or chloride levels at about 30% of Illinois coal mine NPDES sites appear to be unaffected by precipitation. Additional comparisons of sulfate and chloride versus precipitation are presented in Figures 5.9, 5.10, and 5.11. In all these examples, there is poor correlation between precipitation and sulfate/chloride concentration levels.

In case of underground mine #6 (Figure 5.9), the sulfate concentrations were at or below 200 mg/L until the 42nd month. Subsequently, sulfate levels increased precipitously at a logarithmic rate, which is characteristics of acidification of a pyritic source, in this case, a waste disposal area. In Figure 5.10, chloride concentrations are consistently below 200 mg/L after 42nd month except for one spike that is either attributed to a flushing event or data error. Note in Figures 5.9 and 5.10 that at the same site the sulfate concentrations have gone up with time while chloride levels
have gone down. Chloride reductions are expected because the maximum amount of chloride is released when the material is crushed in the mining, material handing, and coal processing activities. As the material is leached by dust control and processing water during these activities the chlorides salts are mobilized and will migrate away from the pile due to the high mobility of the chloride ion. Although desiccation and subsequent rewetting by precipitation can create spikes in the chloride discharge (Figure 5.7) precipitation had limited effects on the chloride discharge level in mine #6 (Figure 5.10). Similar case could be also made for sulfate data from underground mine #9 (Figure 5.11). The steady downward trend in sulfate for mine #9 may be due to operation or reclamation activity at the site such as the covering of aging, sulfate-generating refuse with compacted fresh refuse, placement of a final reclamation cap, inundation of refuse materials, or the addition of a new dilution water source. Finally, majority of data analyzed in this study point toward direct correlation between precipitation events and subsequent alteration in sulfate and chloride levels. There are a few exceptions that may have been caused by miscellaneous factors such as site geochemistry, hydrology, depth of mining, and other operational practices.

Figure 5.9. Sulfate concentration vs. precipitation for underground mine #6.

Figure 5.10. Chloride concentration vs. precipitation for underground mine #6.
A more detailed correlation is needed than was possible in this study to better define the variables that can affect sulfate and chloride discharges as a function of time. Some controlling factors such as local precipitation variations, pumping rates and other operational activities are not recorded. This would limit the degree of correlation, which could be made with regard to sulfate and chloride concentrations in mine discharge water. Water quality data collected in this report are shown in Table 5.1. It should be noted that this data should be considered preliminary reconnaissance sampling and as such inconclusive. It is presented here as an indicator of the type of study needed to evaluate the impacts of factors such as site-specific geochemistry and operational conditions on sulfate and chloride discharge levels.

Table 5.1. Preliminary intra-plant water sampling in selected Illinois coal mines.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH* (S.U.)</th>
<th>Sulfate* (mg/L)</th>
<th>Chloride* (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine I - Prep plant intake water (slurry decant)</td>
<td>8.28</td>
<td>431</td>
<td>552</td>
</tr>
<tr>
<td>Mine I – Slurry</td>
<td>8.21</td>
<td>451.7</td>
<td>899.3</td>
</tr>
<tr>
<td>Mine II - Prep plant intake (slurry decant)</td>
<td>8.02</td>
<td>1,957</td>
<td>52.8</td>
</tr>
<tr>
<td>Mine II - Slurry</td>
<td>7.66</td>
<td>2,371</td>
<td>101.9</td>
</tr>
<tr>
<td>Mine VII - Plant intake (slurry decant)</td>
<td>8.17</td>
<td>1,136</td>
<td>89.5</td>
</tr>
<tr>
<td>Mine VII - Slurry</td>
<td>7.72</td>
<td>1,293</td>
<td>110.8</td>
</tr>
</tbody>
</table>

*All analyses by Standard Labs, Inc., Freeburg, IL.

5.5 Recommendations for Discharge Water Quality Data Collection and Analyses

In the event that a sediment basin is repeatedly showing exceedances of water quality criteria, intra-plant water sampling can be conducted to determine the basin-specific flushing characteristics and to improve discharge management techniques. This sampling could be expanded beyond the data illustrated in Table 5.1 to include additional water holding ponds within the closed loop system (sediment basins, mine
pump discharge holding ponds, thickener decant holding ponds, etc.), fresh water sources (impoundments, well discharge or agricultural drain sources) and refuse area under-drain or toe drain discharge. This information could identify individual sources of chloride and sulfate within the mine to target for control by GMP application and would be useful in planning blow-down of high sulfate and/or chloride water within the closed loop and the amount of on-site or in-stream mixing dilution required. Additional samples could also be taken between precipitation cycles to evaluate the flushing activity within the operation and its impact on closed loop systems water quality. This type of data could also be used to evaluate the hydrologic characteristics, of the site, such as the lag between precipitation and flushing of sulfate and chloride and its impact on discharge levels.
6.1 Introduction

During the course of this study, visits were made to both underground and surface coal mining facilities to survey the refuse management practices. These visits were made to observe mining, processing, and coarse/fine coal processing refuse disposal operations and water management at the site. This helped to develop an understanding of the relationships that exist among all of the above activities as they impact sulfate/chloride discharges from the mine. During the visits insights from professionals at each mine were obtained and synthesized. The visits also allowed the project team to observe and assess good and not-so-good management practices and develop an inventory of proven good management practices for operators throughout the State to consider for implementation. The approach used in the visits and pertinent observations are presented here.

6.2 Methodology

A questionnaire was developed to collect information on mining, processing, refuse management and water management practices. The response of a coal mine operator to the questionnaire formed the foundation of the good mining practices (GMPs’) discussion at each mine in addition to review of permit documents and an analysis of their sulfate and chloride discharge trends. Total of eight (8) mines, representing over 90% of coal production in Illinois were visited. The visit to each mine lasted 4-6 hours excluding travel time. The visit included discussions with the assigned engineer, visit to the waste management operations, collection of coal processing waste samples, and water quality samples from strategic locations such as input and output of the processing plant, decant water from the slurry pond, and water from the drainage ditches, if appropriate. One surface coal mine and seven underground mines were visited. The mines visited represent a good cross-section of various types of coal mining and refuse disposal operations in the state. The group of mines visited had new and old mines; low and high sulfate discharge mines; and low and high chloride discharge mines.

6.3 Mine I: Survey Observations

(i) Mine and processing plant operations: Mine I is an underground mine in west-central Illinois, that had a production of about 2 million tons of clean coal per year. It mined Herrin seam at depth of about 325 feet. The coal is overlain by Anna black shale-limestone in some areas and Energy shale in other areas. The coal processing waste consists of 20% in-seam material and 80% out-of-seam dilution, primarily from roof strata. The in-seam pyritic sulfur content is 2.6%, organic sulfur content is 2.64% and sulfates are 0.25%. There is small variability in sulfur content throughout the mine. The processing plant recovery is about 70% and 0.85 million tons of refuse is
generated every year (including CCPW and FCPW). The distribution of CCPW to FCPW is about 3:1.

(ii) CCPW and FCPW management: Currently, the mine has two coarse refuse disposal areas and two slurry disposal areas (Figure 6.1). The old coarse refuse pile is on the NW side and the new coarse refuse pile is on the NE side of the mine permit area. The older of the two slurry disposal areas is located on the SE side of the old coarse refuse disposal area and it has been capped using FBC byproducts. The byproducts are hauled back from 10 different sources and they provide alkalinity for on-site AMD neutralization. Previously, coarse refuse was mixed with byproducts in bulk to amend the neutralization potential (NP) for the CCPW. Currently, FBC products are managed separately from CCPW. However, highly alkaline water from the byproducts is available for use to neutralize AMD, if needed.

![Figure 6.1. Mine I aerial photograph.](image)

(iii) Water management: The water management network employs a closed loop system, which maintains and isolates all AMD and byproducts disposal runoff within the active operation. Coal processing plant receives fresh water from a nearby creek and also from the run-off circuit. Run-off water from the old refuse pile reports to a settling pond. A few structures screen the run-off before it is pumped to the clarified pond. Excess water from the coal processing plant is used to deliver byproducts in a slurry form to the disposal area. Decant water from the fine refuse disposal areas on the NE side of the permit acts as the surface make up water for ash delivery. Water
coming out of the preparation plant is also used to deliver the FCPW into the slurry pond on NE side of the mine permit area. Coarse and fine refuse samples were collected from this mine site along with preparation plant intake water.

6.4 Mine II: Survey Observations

(i) Mine and processing plant operations: Mine II is a surface mine in southern Illinois that produces about 4 million tons of clean coal per year and 1 million tons of coal processing waste per year. The mining depth is 120 feet and the coal seam (Murphysboro seam) being mined has thickness of 6 feet. The mine has shale and limestone as roof and claystone as floor. Coarse refuse (CCPW) at this site is a mixture of hard, high ash-content coal known as “bone coal”, parting and roof shale (carbonaceous black shale), and a considerable amount of floor rock (coarse, light gray-colored claystone fragments). A large amount of coarse pyrite was observed forming bands in mined coal. Fine refuse (FCPW) was also rich in pyrite fines as observed around the FCPW pipe discharge area. A portion of the coal from this site is mined with a high-wall miner system from a box cut. This system employs an underground mining-type continuous miner that is remotely operated from the surface. As a result this mine produces coal that has a higher out-of-seam dilution than a typical Illinois surface mine.

(ii) CCPW and FCPW management: CCPW materials at this mine are hauled back into adjacent surface mine pits before covering them by overburden spoil. Overburden material is hauled back in trucks and placed on the top of CCPW, before covering both the refuse and overburden with stockpiled top-soil and sub-soil. Overburden material separates based on size due to end dumping from haul trucks. Large (mostly alkaline limestone material) rolls to the bottom while the finer material (more likely to be acid-producing) stays close to the top of the embankment. The slurry cell is located over the west side of the mine and receives slurry from the preparation plant (Figure 6.2). No solid or water discharge occurs at NPDES points from this mine permit area. Slurry disposal occurs in the northernmost incline only.

Preparation plant is rated at 550 ton/hour. FCPW material is pumped as 7% solids slurry into an old haulage ramp from the open pit. The slurry fines segregate with distance from the discharge point. Pyrite and other heavier fines segregate near the top of the old haul ramp. Significant amounts of FCPW material was exposed to atmosphere but it was in a saturated or semi-saturated condition, closer to the point of discharge. Refuse and water quality samples were collected from this mine for analyses.

(iii) Water management: One large diameter pipe pumps 7% solids concentration slurry into a box-cut slurry cell. The decant water from the FCPW is pumped back to the preparation plant through three large diameter pipelines. Pumping is also done from the box cut and high-wall faces, and water from these sources goes to different sumps. Typically, no slurry fines or water discharge occurs at NPDES points from
this mine permit area due to the presence of an earthen barrier across the impoundment and the large amount of percolation through the spoils.

Figure 6.2. Mine II aerial photograph.

6.5 Mine III: Survey Observations

(i) Mine and processing plant operations: Mine III is an underground mine in southern Illinois that mines 2.4 million tons of clean coal per year. It mines Herrin seam (6.5 feet thickness) from depth of 190-250 feet. The coal seam has black shale as immediate roof and claystone as floor. The seam also has a 3-inch band of shale/pyrite and mines out-of-seam dilution of 0.5 – 1 foot. The mine generates about 1.5 million tons of total refuse with FCPW to CCPW ratio of 7:12.

(ii) CCPW and FCPW management: A large amount of FCPW and CCPW, produced by an earlier operator of this mine, has been deposited in a refuse pile on the SE side of the mine permit (Figure 6.3). This refuse disposal area has been capped and reclaimed, and is now outside the current mine permit area. Currently, the mine has four operating refuse disposal areas. There are two refuse disposal areas on the north side of the mine permit area and receive the FCPW. The northern most refuse cell (#3, Phase II) is currently receiving CCPW as well. The refuse cell #1 has been completely covered and reclaimed. The refuse disposal area #2 is also in the process of being covered. At present, this area of the mine permit is being covered with CCPW. This area also has a haul road made up of gob materials that has been compacted. The slurry disposal is currently being done at the middle southern end of
slurry cell #3. A new slurry cell surrounded by an earthen embankment is under construction at this site.

![Mine III aerial photograph.](image)

Figure 6.3. Mine III aerial photograph.

(iii) Water management: The decant water from both active slurry ponds goes to the re-circulation lakes through spillways and the water is used by the preparation plant. Only during heavy precipitation events this mine discharges water through the only NPDES point. Both refuse and water samples were collected from this mine and analyzed.

6.6 Mine IV: Survey Observations

(i) Mine and processing plant operations: Mine IV is an underground coal mine in southern Illinois that mines about 5.5 million tons of clean coal per year from both the Herrin and Springfield seams (average 6 feet in thickness), using a longwall mining method. The mine generates CCPW and FCPW in the ratio 3.2:1. The Herrin coal seam has black shale as roof with intermittent streaks of limestone and the Springfield coal seam has dark gray shale as roof.

(ii) CCPW and FCPW management: The mine has two refuse disposal areas in addition to multiple sediment and recirculation ponds. The western refuse disposal area has currently reached its capacity and is being closed (Figure 6.4). The eastern refuse disposal area receives FCPW into its impoundment structure constructed with CCPW. The ultimate height of both the refuse disposal areas is about 120 feet.

(iii) Water management: The mine pumps about 1 million gallons/day mine water and utilizes a combination of multiple holding and dilution ponds that are used to dilute high concentrations of chlorides inherent in the mine water. The dilution ponds are
critical for the mine to stay in compliance, as the mine has to discharge water on a regular basis due to its high water pumpage rate.

Figure 6.4. Mine IV aerial photograph.

6.7 Mine V: Survey Observations

(i) Mine and processing plant operations: Mine V is an underground room-and-pillar operation in East Central Illinois that mines Herrin seam for clean coal production of 2.7 million tons/year and has a coal refuse production of 1.1 million tons/year. CCPW and FCPW are generated in the ratio 2:1 at this mine. The mine has out-of-seam dilution from shale roof (4-inch) and claystone/underclay floor (4-inch). There is also in-seam dilution from the coal seam in the form of thin pyrite bands.

(ii) CCPW and FCPW Management: The mine has one large refuse disposal area (Figure 6.5). The preparation plant utilizes belt-presses to dewater the FCPW (slurry) fines. The dewatered fines (60% solids) are hauled into the refuse disposal area and disposed in the impoundment structure constructed using coarse refuse. This mine is unique in terms of its co-disposal of coarse and dewatered (filter pressed) fine refuse materials.

(iii) Water management: Run-off water from the refuse disposal area is diverted through collection drains to the fresh water/re-circulation lake to be used up by the preparation plant. The mine discharges water through the only NPDES discharge location only in case of heavy precipitation events. A large fresh water lake is available for dilution of water high in sulfate and chloride.
6.8 Mine VI: Survey Observations

(i) Mine and processing plant operations: Mine VI is an underground longwall coal mine in west-central Illinois that mines about 3 million tons of clean coal/year. The mine currently mines Herrin coal seam with thickness ranging from 5-6 feet. Out-of-seam dilution from floor and roof vary from about 1.0 to 2.5 feet. Most of this out-of-seam dilution is from the floor (claystone) and to a lesser extent from the roof (Anna black shale). Previous mining in Herrin No. 6 Coal seam with continuous miner operations also included considerable out-of-seam dilution. However, the refuse material then was derived primarily from the overlying dark Anna shale, and a small amount of underclay/claystone from the floor rock. Therefore, the older refuse facility contains considerably more carbonaceous shale from the roof than claystone from the floor rock.

(ii) CCPW and FCPW management: Six separate coal refuse disposal areas are located on the site. Four disposal areas have been capped and reclaimed. The fifth refuse area is in the process of reclamtion (Figure 6.6). The capping material for this refuse area is derived from the processing of coal and out-of-seam dilution materials from the longwall mining operations. Hence, there is large amount of claystone present that should be helpful in capping the older facility. Coarse material is placed by off-highway end dump trucks and spread with a dozer into an abandoned slurry cell. The newest refuse disposal area (i.e. sixth) has two areas separated by a berm and joined by a culvert (Figure 6.6). The berms of this refuse disposal area are built with CCPW (coarse refuse) using a sheep-foot roller compactor. The first area
receives slurry fines through a manifold, after flocculants have been added to it. This speeds up the fines’ settling process and helps prevent channels and redistribution of the pyrite-rich coarse FCPW fraction in the discharge area. A large fresh water lake is available for dilution of water high in sulfate and chloride. Refuse samples were collected from this mine for analyses.

(iii) Water management: The water removed during the slurry settlement process goes to second area of the refuse disposal area through a culvert. The decant water is then re-circulated back into the processing plant through a re-circulation lake.

Figure 6.6. Mine VI aerial photograph.

6.9 Mine VII: Survey Observations

(i) Mine and processing plant operations: Mine VII is a moderate-sized combination of underground and surface mine with an associated processing plant and a coal refuse disposal facility mine in southern Illinois. At full production this operation will produce over 2.0 million tons of clean coal per year. Mining involves a combination of three (3) production units, two (2) room-and-pillar mining operations using continuous miners (one operating unit each in the No. 5 and No. 6 seams – 60% of
the production) and an adjacent surface mine (No. 6 and No. 7 seam providing 40% of the production). Surface coal production at this mine is expected to decline rapidly by 2008 unless additional reserves are acquired.

(ii) CCPW and FCPW management: The coal processing plant processes raw coal at the site with all the waste disposed onsite in the surface mine pits (Figure 6.7). This mine previously injected a mixture of CCPW and FCPW into an abandoned underground mine. Currently, CCPW is intermixed and disposed with spoil in the surface mine as backfill. The existing FCPW facilities is done in an abandoned open surface mine pit. A large combined fine and coarse coal refuse stockpile is planned on the site. The planned facility will be about 25–30 feet high and will consist of fine coal refuse encapsulated by a coarse refuse embankment that will eventually be capped by coarse material. The planned facility is intended to last from 6-7 years or the remaining life-of-mine.

(iii) Water management: Decant water from the FCPW disposed in the surface mine cuts are routed back to multiple holding ponds inside the mine permit area, before it is re-circulated back into the coal preparation plant (Figure 6.7). Water pumped from the surface mine cuts are also pumped into the holding ponds for use by the preparation plant. Multiple NPDES discharge points discharge excess run-off from within the mine permit area in case of heavy precipitation.

Figure 6.7. Mine VII aerial photograph.

6.10 Mine VIII: Survey Observations

(i) Mine and processing plant operations: Mine VIII is a 25-year old underground mine in Central Illinois that mines both Herrin and Springfield seams at depths varying from 280 – 320 feet. The mine produces 3.3 million tons of clean coal per
year and generates 1.25 million tons of coal refuse every year. The source of out-of-seam dilution is black shale (roof), pyrite (roof) and claystone (floor). In-seam dilution is in the form of pyrite and shale bands (partings) present in coal.

(ii) CCPW and FCPW management: Only one refuse disposal area is utilized by the mine for the coarse and fine refuse that are generated (Figure 6.8). The coarse refuse is mixed with FBC fly ash and a small amount of FBC bottom ash that is compacted to form the embankments for the FCPW. The CCB material is mixed in the ratio of 4:1 CCPW to FBC byproducts ratio. FBC byproducts from multiple sources are used. The FCPW is deposited using a moveable slurry discharge pipeline that submerges slurry fines under water to the extent possible and eliminates large delta formations and exposure of slurry fines to weathering.

(iii) Water management: The mine uses three sediment/re-circulation ponds to receive the run-offs and decant water from the refuse disposal areas. Heavy precipitation events may result in mine discharge through one or more NPDES discharge locations inside the mine permit area. Fresh water dilution is aided by the capture of the discharge from a large agricultural field drain. Water from the perimeter sedimentation basins is routinely pumped into the recirculation system to supply additional dilution.

![Figure 6.8. Mine VIII aerial photograph.](image-url)
6.11 Refuse Quality Analyses Results

Within the imposed funding and time constraints, only a limited number of samples (one or two samples for each coal processing circuit from 4-5 sites) were collected and analyzed to evaluate the acid-forming potential. Coarse and fine coal refuse samples collected were analyzed for parameters such as total sulfur, pyritic sulfur, total acidity, neutralization potential and paste pH. The summarized results from this limited sample set are presented in Table 6.1. Based on this limited testing the coarser fractions of the coarse refuse generally possess a larger potential acidity. Overall, all coarse refuse had larger potential acidity than the fine refuse. Also, there was large difference between the potential acidity and neutralization potential for CCPW (coarse coal refuse) and fine coal refuse (FCPW) that represented composite slurry collected from the thickener underflow. This data suggests that the coarse refuse will start to acidify and generate sulfate rich leachate much sooner than the fine coal refuse. Additional more representative testing is required to evaluate fractional refuse geochemistry.

Table 6.1. Summarized geochemical properties of Illinois coal refuse (Limited sampling).

<table>
<thead>
<tr>
<th>Refuse Stream</th>
<th>Sulfur Content (%)</th>
<th>Paste pH</th>
<th>Tons of CaCO3</th>
<th>Percent of ROM Coal</th>
<th>Tons of Refuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse circuit</td>
<td>Total: 8 – 12</td>
<td>6</td>
<td>240 - 360</td>
<td>15 - 25</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Pyritic: 8 - 12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle size circuit</td>
<td>Total: 6 – 8</td>
<td>7</td>
<td>170 - 230</td>
<td>20 - 40</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Pyritic: 5.5 - 7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine size circuit</td>
<td>Total: 6 – 7</td>
<td>7</td>
<td>170 - 200</td>
<td>30 - 100</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Pyritic: 5.5 - 6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite coarse refuse</td>
<td>Total: 6 - 7</td>
<td>7.5</td>
<td>170 - 200</td>
<td>30 - 90</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Pyritic: 5.5 - 6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slurry fines</td>
<td>Total: 1.5 - 2</td>
<td>45 - 62</td>
<td>40 - 55</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

6.12 Good Refuse Management Practices

During the course of this study field site observations and discussions with mine personnel identified a number of refuse management practices identified as “good practices.” These are summarized under the coarse coal refuse and fine coal refuse subheadings.

(i) Coarse refuse good management practices:

- Systematically covering of older (> 3-6 months old) coarse coal refuse with fresh refuse.
- Limited end-dumping followed by compaction of coarse refuse in berms and benches.
- Mixing of alkaline CCB materials, such as FBC ash, with coarse refuse and co-disposal for construction of berms and benches of refuse disposal areas.
• Co-disposal of dewatered FCPW and CCPW.
• On-site CCB material disposal and use of alkaline fly ash decant water to treat coarse refuse run-off, sulfate–rich water.
• Selective disposal of CCPW near the bottom of the surface mine cuts and covering it with overburden spoil in a timely manner.
• Construction of smaller refuse disposal areas and their more contemporaneous reclamation.
• Incorporating sufficient alkaline amendment in the upper portions of graded CCPW and putting a soil cover.
• Large water storage areas to provide for dilution for chloride discharges.

(ii) Fine refuse good management practices:

• Using multiple FCPW discharge points that avoid delta formation of coarser materials.
• Systematically moving FCPW single discharge point at intervals to submerge problematic pyrite-rich fine materials under water.
• Maintaining 1-2 feet water cover over FCPW pond and maximizing submersion of slurry fines.
• Dewatering of FCPW and co-disposal with CCPW refuse.
• Establishing multiple holding/dilution ponds to store high sulfate and chloride water.
• Disposing FCPW in old surface mine cuts and either covering them with spoil or permanent water cover in a timely manner.

(iii) Water handling: good management practices:

• Application of dilution from large onsite or offsite fresh water impoundments.
• Recycling runoff from sedimentation basins as low sulfate and chloride dilution water from areas in which the reclamation has been completed.
• Collections of groundwater discharge from agricultural field drains for use as a dilution water source.

Some of the above good management practices can not be implemented at every site depending on site-specific conditions. For example, co-disposal of CCPW and CCBs is possible only if back haul contract can be developed. Labor contracts may not allow co-disposal at some sites. Lack of available space may not allow slurry pond development. Surface topography and lack of surficial materials may not allow contemporaneous reclamation. The ratio of CCPW to FCPW may force operators to alter their good waste management practices. Current FCPW dewatering and CCPW co-disposal technology is cost prohibitive.

Although some of these practices were observed during visits at selected mines, these so-called “good practices” were in most cases not common practices. The following comments are pertinent related to management practices that directly affect sulfate
and chloride discharges from mine locations. Additional attention to these comments by mine operators should reduce sulfate and chloride discharges from their sites.

- There is potential for operators to better manage CCPW, FCPW and water. Operators should spend more time in planning, implementing, and monitoring waste disposal operations.
- Leaving large un-reclaimed refuse management can negatively affect sulfate and chloride discharges. Several operators demonstrated significant reduction in sulfate discharges when large un-reclaimed areas were partially or fully reclaimed.
- Use of planned compaction activities, including placement in the proper lift thickness (as determined by compaction equipment and material characteristics) and applying the necessary compaction equipment and tests, was limited at several sites during refuse disposal facility construction.
- The covering of weathered and aged coarse refuse by fresh refuse was not common.
- Operators in a number of cases push weathered and presumably acidified CCPW into FCPW (slurry disposal areas). This practice may increase sulfate generation by two processes: 1) direct acidification of the re-exposed slurry above the water table and capillary zone, and 2) chemical weathering of contained pyrite by ferric iron to the extent it can seep from overlying acidified material.
- Operators commonly build roads and water control and vehicle safety berms with CCPW. Although the roadway surfaces of the CCPW gets well compacted by truck traffic, the outer areas of the road and safety berms may remain uncompacted. Acidification of refuse and subsequent release of sulfate can occur in these areas. The discharges from these structures typically feed into slurry and sedimentation ponds and can negatively affect sulfate concentrations.
- The practice of ageing and weathering of CCPW to reduce pyrite contents to manageable levels for vegetation are appropriate. Although the majority of precipitation will occur as runoff, some may infiltrate into the refuse pile where ferric iron in the leachate may weather more pyrite. This process can be driven by water head changes due to either seasonal fluctuations of the water table within the pile or the presence of under drains (constructed to collect percolation). Unless most of the sulfate liberated in the aging process is retained as insoluble minerals the aging process will liberate additional sulfate, which may require dilution before or after discharge. One method to limit sulfate generation could be to add agricultural limestone as appropriate. These additions neutralize acid, adjust the pH, and provide an abundance of calcium ions. For sulfate retention within the refuse pile it must be assumed that gypsum [CaSO₄ * H₂O] is the principal sulfate mineral produced during the aging process and that this mineral will remain stable indefinitely (Ca²⁺ and SO₄²⁻ remains supersaturated). However, due to the moderately high solubility of this mineral, sulfate can remobilize by two methods: 1) where a lower concentration gradient is developed, such as due to dilution by recharge water with a low ionic strength or the exhaustion of the calcium source (i.e. calcite in the refuse or limestone additions), and 2) by the “ion pairing effect”.

6.13 Relative Importance of Different Current Refuse and Water Management Practices Affecting Sulfate Discharges

The project team identified and prioritized current waste management practices that contribute to increased sulfate/chloride discharges. Then, the team assessed relative importance of these practices to increased sulfate/chloride discharges. Based on project team’s experience, ratings were assigned to inappropriate coarse-refuse management practices; fine refuse management practices and water management practices. Finally, good management practices identified are briefly described here for mine operators to use based on each mine’s needs. Each good practice addresses one or more than one inappropriate practices.

Table 6.2 lists the inappropriate coarse refuse management practices observed in the Illinois coal mining industry. Similarly, inappropriate practices encountered in fine refuse management and water management are presented in Tables 6.3 and 6.4. Majority of the inappropriate practices have been identified by many technical experts prior to this study and their research is included in references.

Table 6.2. Current CCPW management issues

<table>
<thead>
<tr>
<th>No.</th>
<th>Practice</th>
<th>Contribution to Sulfates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large areas exposed to weathering resulting in acidification</td>
<td>VERY SIGNIFICANT</td>
</tr>
<tr>
<td>2</td>
<td>Inadequate compaction of refuse allowing air/water percolation and leaching of sulfate salts</td>
<td>SIGNIFICANT</td>
</tr>
<tr>
<td>3</td>
<td>Lack of geochemical data of refuse</td>
<td>MINIMAL</td>
</tr>
<tr>
<td>4</td>
<td>Mixing of acidified coarse refuse into deposited slurry ponds</td>
<td>MODERATE</td>
</tr>
<tr>
<td>5</td>
<td>Lack of concurrent reclamation</td>
<td>SIGNIFICANT</td>
</tr>
<tr>
<td>6</td>
<td>Inappropriate physical characteristics of coarse refuse from compaction point of view</td>
<td>MINIMAL</td>
</tr>
<tr>
<td>7</td>
<td>Inappropriate technology for compaction evaluation</td>
<td>MINIMAL</td>
</tr>
</tbody>
</table>

Table 6.3. Current FCPW management issues

<table>
<thead>
<tr>
<th>No.</th>
<th>Practice</th>
<th>Contribution to Sulfates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slurry exposed to weathering and oxidation (assumes &gt;75% saturated vertical stratification)</td>
<td>MODERATE</td>
</tr>
<tr>
<td>2</td>
<td>Slurry discharge points are not frequently moved producing unsaturated deltas of concentrated pyritic coarse materials that acidify</td>
<td>MINIMAL</td>
</tr>
<tr>
<td>3</td>
<td>Acidification initiated in coarse refuse berms promote acidification of unsaturated slurry</td>
<td>MINIMAL</td>
</tr>
</tbody>
</table>
Table 6.4. Water management practices.

<table>
<thead>
<tr>
<th>No.</th>
<th>Practice</th>
<th>Contribution to Sulfates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The existence of large areas of un-reclaimed coal refuse limits the amount of run-off water with low sulfate and/or chloride that can be used for on-site dilution.</td>
<td>SIGNIFICANT</td>
</tr>
<tr>
<td>2</td>
<td>Coal processing is done with high sulfate and/or chloride water allowing salts to form on wetted surfaces of coal product and coal refuse. These salts are rapidly released by rewetting after placement in refuse facilities.</td>
<td>MINIMAL</td>
</tr>
<tr>
<td>3</td>
<td>Since releases of high sulfate and/or chloride waters are infrequent, their concentrations increase in water system.</td>
<td>MINIMAL</td>
</tr>
<tr>
<td>4</td>
<td>High and low sulfate and/or chloride waters are mixed preventing the latter from being used for on-site dilution.</td>
<td>MINIMAL</td>
</tr>
</tbody>
</table>

These observations led the project team to formulate recommendations in two categories: proven good management practices that would immediately help operators reduce sulfate discharges, and conceptual good management practices that require some development but would help operators minimize long-term liability for sulfate discharges.
CHAPTER 7
PROVEN GOOD MANAGEMENT PRACTICES

7.1 Introduction

Based on all the project related survey tasks such as preliminary literature review, review of permit application documents, visits to mines and refuse management facilities, and discussion with technical experts and industry professionals, the study team identified good management practices that may be used by the Illinois coal mine operators to maximize their control on sulfate and chloride discharges. These approaches were discussed by the study group with the industry professionals. Almost all of them have proven to be effective in different field conditions in Illinois and adjoining states mining high sulfur coal. Coal mine operators should be encouraged to incorporate these practices into their waste management, water management, and reclamation activities to minimize sulfate and chloride discharges. Due to operational and geochemical variations between mine sites the management practices presented below may not be economically applicable in all cases.

The group also identified several good management practices concepts that need further development through pilot-scale and field-scale demonstrations. These concepts may need collaborative effort from industry and technical experts to demonstrate their technical and economic effectiveness. These are discussed in Chapter 8.

7.2 Proven Good Management Practices (PGMPS)

The near-term management practices included in this chapter are divided into coarse refuse and fine refuse categories. The appropriateness and effectiveness of each management practice will vary from site to site based on factors such as precipitation, site hydrology, and refuse geochemistry. These practices affect acid sulfate discharges by delaying or preventing the sulfur cycle as discussed in Chapter 2. Most importantly, the discussed practices are based on the premise that minimizing acid sulfates and chloride generation is more environmentally effective and economically desirable than perpetually treating affected water, or falling short on compliance.

7.3 Coarse Coal Processing Waste Management

(i) Proactive Management Practices (Site-specific: Implement as feasible)

- Maximize extent and distribution of un-oxidized, fresh refuse: Fresh coarse coal refuse contains pyritic sulfur and will ultimately generate acid salts and acid runoff. Depending upon the availability of naturally occurring carbonates (alkalinity), fresh refuse may not typically generate acidic leachate for 3-12 months. This “critical period” must however be established for each mine site based on refuse geochemical and management characteristics as well as precipitation and weather patterns such as temperature, wetting and drying. Uncontrolled aging and weathering of refuse, due to exposure to oxygen and
moisture in un-reclaimed refuse areas, will initiate pyrite oxidation and generation of acids salts. Therefore, un-reclaimed exposed surfaces of refuse disposal areas should be covered with fresh refuse within 3-12 months to minimize initial refuse acidification, and/or minimize the extent of aged, acidified refuse. Timing and placement of fresh refuse will depend upon refuse geochemistry, aging/weathering characteristics of refuse, compaction achieved, and site specific constraints or opportunities available within a refuse disposal area management plan.

- Design refuse disposal areas to maximize fresh refuse disposal and concurrent compaction: Refuse disposal areas and management practices are typically designed prior to actual disposal. Therefore, active refuse disposal areas should be designed to maximize fresh refuse distribution. Refuse disposal areas should be designed, (when feasible/to the extent possible) to allow future access to slopes, benches, and faces for placement of un-oxidized fresh refuse, compaction, and/or application of alkaline amendments. Fresh refuse should be graded and compacted before acidification begins. Side slopes should be compacted wherever feasible, as air and water infiltration in these loose materials may lead to rapid onset of pyrite oxidation, and acid runoff/seep generation.

- Minimize long-term end-dump storage areas to prevent acidification: End-dumped and un-compacted coarse refuse piles acidify rapidly. Long-term, end-dump refuse storage areas should be avoided. Fresh refuse should be compacted in berms and benches (in-place compaction) to minimize and/or delay the onset of acidification. End-dumped fresh refuse should be graded and compacted in six-inch lifts before acidification is initiated (typically less than 3-12 months following disposal). To prevent the spread and introduction of acid ‘Hot Spots”, acidified, end-dumped refuse should not be graded and mixed with fresh refuse.

- Acidified refuse areas should receive alkaline amendment to restore non-acid conditions: Alkaline amendment may be required if an operator is unable to prevent acidification of refuse areas and acid runoff to sedimentation/recirculation ponds and eventually, to the NPDES discharge point. To maintain NPDES compliant discharge quality, and/or to minimize perpetual treatment costs alkaline amendments should be applied to acidified portions of refuse disposal areas (Figure 7.1). Simple field observation of acids salt formation, verified with pH paper test strip, or a pH meter measurement of refuse leachate can quickly identify the extent of acidified refuse zones. Acidic (pH < 6) refuse zones, should be treated with alkaline amendment applications to restore non-acidic conditions and minimize further acidification and sulfate generation. Alkaline amendments such as agricultural limestone, fly ash of various forms, alkaline bottom ash, steel slag, lime kiln dust (LKD), cement kiln dust (CKD), etc. may be used to maintain or restore non-acid conditions. Alkaline amendment applications should establish a minimum of 10 ton/1000 ton net neutralization potential (NNP) alkalinity on the acidified refuse disposal area surfaces, before fresh refuse is deposited. Maintaining and restoring up-slope alkaline conditions should also minimize acid
run-off from initiating acidification of down-slope refuse.

Figure 7.1 (a) & (b) Alkaline amendment (agricultural lime) broadcasts

(ii) Preventative Management Practices (Site-specific: Implement as feasible)
- Alkaline amendment addition in refuse zones that have not recently (less than 3-12 months) received fresh refuse: Similar to alkaline amendment of acidified refuse to restore alkalinity, application of alkaline amendments should be practiced when necessary to maintain non-acid (pH>6.0) conditions and establish a 10 ton/1000 ton NNP balance in those areas, where no fresh refuse has been added in the previous 3-12 months. A preventative alkaline amendment can
maintain non-acidic conditions and minimize or delay the initiation of acid generation.

- Neutralization of uncontrolled acid/sulfate-run-offs from refuse disposal areas: Uncontrolled acid salt generation from aged and weathered refuse zones, and subsequent runoff to surface drainage networks and holding ponds contribute to adverse water quality. Evaporation within detention ponds concentrates sulfates, which may infiltrate into ground water through unlined drains and basins. If concentrated sulfates are circulated through the coal preparation plant make-up water back to the refuse disposal area, further degradation of water quality and refuse geochemistry can occur. To minimize adverse sulfate concentration all acid run off should be neutralized immediately using appropriate alkaline amendments.

- Establish Alkaline Recharge Trench (ART) infiltration zones in out-slope run off and erosion control channels: ARTs can be designed and installed concurrent with the vertical construction of refuse lifts and bench perimeters to manage runoff and control erosion (Figure 7.2). ARTs represent a preventative vs. treatment technique for controlling acid sulfate discharges. ART installations are based on the simple principle that no above-grade refuse construction or reclamation design completely prevents moisture and air infiltration on upper benches, or faces. Therefore, alkaline recharge trenches provide an alkaline infiltration and infusion system to intercept and counteract the acid seep pathways that can develop on side slopes and toes of coarse refuse disposal areas. Alkaline amendment placement within the trench substrate promotes alkaline infiltration to ameliorate or minimize potential acid seep generation. Suitable alkaline amendments include conventional agricultural limestone as well as CCBs. Alkaline recharge trench designs provide the opportunity for optional future (10-20 year) surface broadcast application of alkaline amendments within the recharge channel coarse rip-rap void matrix.

Figure 7.2. Alkaline recharge trench
(iii) Enhanced Reclamation Coarse Refuse Management Practices (Site-specific: Implement as feasible)

- **Conventional capping**: Conventional capping is the standard reclamation practice in sites permitted under SMCRA [62 Ill Adm. Code Sec 1816.83 (c) (4) (surface mines).and Sec 1817.83 (c) (4) (underground mines)] The best available “soil” cover is used as cap and vegetative rooting medium for final reclamation of coarse refuse disposal areas. A 4-foot minimum cover is required. However, less than a 4-foot cover can be approved depending upon the inherent geochemistry of the underlying refuse materials, or a pre-cover treatment plan that includes alkaline amendment to address residual pyritic sulfur values. To protect final soil covers from upward acid contamination, and to enhance the acid-base balance of the refuse surface oxidizing zone, alkaline amendment incorporation should continue to be used. A minimum 9-inch thick alkaline-enhanced coarse refuse zone should be established before applying a final soil cap of greater than 2-feet. Alkaline amendment incorporation within the upper 9-inch of the final graded coarse refuse pile is necessary to neutralize existing acidity of the oxidized zone, restore alkalinity, eliminate acid run-off, and to provide sufficient alkalinity for long-term soil cover protection and acid seep abatement. Alkaline amendment rates are based on a minimum of 31 tons CaCO$_3$ equivalent / 6-inch acre slice / 1% pyritic sulfur adjusted for an effective treatment depth designed to maintain non-acid conditions down to depth of ~1-2-foot. The amendment rate is generally derived from IDNR’s evaluation of the entire range (min. – max.) of pyritic sulfur values with the adjustment (~4x) based on the maximum pyritic sulfur value present. If a single alkaline amendment application approach is used, it is critical that “excessive” amendment rates are specified to ensure that alkaline infiltration and flushing are maximized to maintain a non-acid environment on the refuse surface. To maximize alkalinity effectiveness, a period of controlled aging and weathering of refuse surfaces is recommended to ensure that the natural kinetics of decreased pyrite oxidation rates (Phase II) have reached the equilibrium of the fixed solubility rate of CaCO$_3$. 

- **Oxidation Management to Enhance Gob Alkalinity**: As previously discussed conventional coarse refuse capping prior to soil covering may only include one alkaline application. However, to address differential rates of rapid pyrite oxidation that occur during the initial phase of refuse aging relative to the low fixed rate of alkalinity release from CaCO$_3$-based alkaline amendments, a period of controlled aging and incremental limestone amendment is extremely beneficial. An incremental alkaline amendment (acidity-abatement) is implemented over 2-3 seasons to develop a non-acid producing weathered coarse refuse surface zone. This method ensures that stable long-term acid–base equilibrium can be maintained thereby minimizing the occurrence of inadequately amended “hot spots” and generation of acid seeps. Incremental limestone amendment application (@ 75 – 100 tons/acre /yr) for 2 – 3 years accompanied by annual direct seeding of a cereal grain (rye or wheat) cover crop on the final graded coarse refuse controls acid generation and erosion, while enhancing alkalinity and organic matter. The presence of “Hot Spots” within the temporary cover crop
provides a “bio assay” indicating zones of rapid pyrite oxidation that can require additional amendment application prior to the next cover crop establishment. The management of pyrite oxidation coupled with incremental limestone amendment practices is the most fundamental approach to decrease absolute pyritic sulfur values from Phase I (acute acid-generating potential) to Phase II (marginal acid-generating potential) manageable reclamation levels prior to applying the soil cover (Figure 7.3).

Figure 7.3. Refuse reclamation: oxidation management - pyrite oxidation vs. release of alkalinity.

7.4 Fine Coal Processing Waste Management

Discharge Management Practices (Site-specific: Implement as feasible)

- Maintain adequate water depth to maximize retention time and differential separation of FCPW (slurry) constituents: Adequate freeboard and water depth should be maintained throughout the slurry basin during active disposal to maximize retention time allowing differential separation of slurry constituents based on their particle size and specific gravity, relative to the decreasing discharge flow velocity downstream from the discharge point. Optimization of single point discharge slurry disposal practices increases retention time, maximizes differential settling, minimizes “black water” return, and minimizes downstream scour and transport of fine grained pyrite contributing to “typical” zones formation (Fig. 7.4) that has been documented in slurry basins throughout the Midwest (Nawrot and Grey 2000). Although the “typical” zones is simply an artifact of most single point (and some multiple point) active disposal practices, the inherent entrapment of free water and saturation of pore spaces throughout most of the slurry basin lower profile maintains anaerobic conditions not capable of supporting pyrite oxidation. While oxidized surface zones (0-6” samples) become acidic exhibiting age associated depletion of pyritic sulfur to < 0.5%, saturated substrates (30-36” samples) remain neutral.
(pH 6.3 – 6.8) and support 4 to 10 x greater pyritic sulfur values (Table 7.1). The acute zones of acid sulfate generation are generally confined to the elevated discharge zone where pyritic sulfur concentrations range from 4 to more than 15%. Decreased pyritic sulfur values in the 7 – 3% range occur further down slope into the Intermediate Zone. Pyritic sulfur values continue to decrease to a 2 – 1% range within the unsaturated slimes in the Decant zone (Nawrot, 1987) where permanent inundation maintains non-acid producing conditions. Extensive characterization of this physical and hydro-geochemical vertical and horizontal gradient within slurry basins has been the basis for implementing the CWRL Incremental Limestone Amendment Process (ILAP) for direct seeding (no soil cover) slurry reclamation alternatives at several mines throughout the Midwest (see next section for further discussion of ILAP).

![Figure 7.4. Typical zonation of physical/chemical characteristics within Midwest coal slurry impoundments (from: Nawrot 1987).](image)

- **Multiple point slurry discharge:** Sequential movement of a single discharge point or use of multiple discharge points can achieve better slurry distribution and maximize storage capacity. Implementation of these discharge management practices has significantly reduced reclamation costs and improved slurry geochemical and physical characteristics such as:
  1. Minimized exposure of the unsaturated course grained pyritic discharge zone to minimize wind erosion and acidification.
  2. Vertically stratified and distributed coarse grained lenses throughout the slurry profile to enhance drainage and dewatering of the slurry fines.
  3. Maximized level fill within the slurry basin to improve the storage capacity; and establish a uniform physical and geochemical substrate to enhance aging and weathering.

- **Incremental Limestone Amendment Process (ILAP) soil cover alternative:** Similar to alkaline enhancement of coarse refuse prior to soil capping, direct seeding of
limestone amended pyrite depleted slurry has been successfully demonstrated as an alternative to soil cover (Nawrot 2004). This is not standard practice in permits approved under SMCRA in Illinois and approval as an experimental practice or variance may be required. To promote dewatering, slurry densification, and pyrite depletion to manageable levels (<1% pyritic sulfur), an initial drawdown of the slurry basin (12 – 18 months) precedes annual limestone amendment applications (@ 50 -75 tons/ac /year). Limestone amendments are generally applied using low ground pressure broadcast spreader equipment. The aged and weathered unsaturated surface profile is direct seeded to establish an annual cover crop for organic enhancement, bioassay “hot spot” delineation, and establishment of excess neutralization potential. Hotspots observed during the first/second seasons are treated with supplemental alkaline amendment. Total alkaline amendment application rates are based on initial refuse geochemistry and the long-term objective of establishing a 175 – 200 ton/ acre NNP for those slurry zones being direct seeded with permanent vegetation establishment such as native warm season grasses.

Table 7.1. Typical geochemical profile of oxidized surface (0-6 inch) and un-oxidized saturated slurry (30-36 inches) samples (annual monitoring average values) from an Illinois Coal Basin 170–acre slurry cell direct seeded using ILAP (from: Nawrot 2004).

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth</th>
<th>n</th>
<th>Soil pH (paste)</th>
<th>Pyritic Sulfur (%)</th>
<th>Potential Acidity (T/1000T)</th>
<th>Neutralization Potential (T/1000T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>0-6&quot;</td>
<td>21</td>
<td>2.7</td>
<td>0.30</td>
<td>9.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.7</td>
<td>2.45</td>
<td>76.6</td>
<td>125.1</td>
</tr>
<tr>
<td>1996</td>
<td>0-6&quot;</td>
<td>20</td>
<td>3.4</td>
<td>0.24</td>
<td>7.5</td>
<td>61.1</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.6</td>
<td>2.59</td>
<td>80.9</td>
<td>40.2</td>
</tr>
<tr>
<td>1997</td>
<td>0-6&quot;</td>
<td>21</td>
<td>4.0</td>
<td>0.30</td>
<td>9.4</td>
<td>120.1</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.5</td>
<td>1.40</td>
<td>43.8</td>
<td>15.1</td>
</tr>
<tr>
<td>1998</td>
<td>0-6&quot;</td>
<td>21</td>
<td>3.9</td>
<td>0.20</td>
<td>6.3</td>
<td>114.3</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.4</td>
<td>2.40</td>
<td>75.0</td>
<td>41.2</td>
</tr>
<tr>
<td>1999</td>
<td>0-6&quot;</td>
<td>21</td>
<td>4.3</td>
<td>0.20</td>
<td>6.3</td>
<td>227.9</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.3</td>
<td>2.13</td>
<td>66.6</td>
<td>50.8</td>
</tr>
<tr>
<td>2003</td>
<td>0-6&quot;</td>
<td>10</td>
<td>6.0</td>
<td>0.34</td>
<td>10.6</td>
<td>236.4</td>
</tr>
<tr>
<td></td>
<td>30-36&quot;</td>
<td>6</td>
<td>6.8</td>
<td>3.81</td>
<td>119.1</td>
<td>50.4</td>
</tr>
</tbody>
</table>
Passive separation of non-pyritic slurry constituents – compartmentalized basins: Differential separation of non-pyritic slurry constituents during active disposal slurry has previously been achieved through passive specific gravity decanting (cross-basin overflow weir) within existing multiple (more than two) surface mine incline basins to produce a non-acid calcareous silt clay “soil cover substitute” (Nawrot et al. 1984). Implementation of passive decant separation requires close monitoring and control of discharge patterns and flow velocities within the primary basin to ensure that slurry over-flow to the secondary non-acid decant portion of the basin remains non-pyritic. Since this practice did not require dewatering or re-handling of ROM slurry discharges, the passive separation of acid producing and non-acid producing slurry was cost effective. The compartmentalization of an existing basin, rather than construction of a new basin, accommodated the design. In addition, no soil cover was required to cap the non-acid portion of the slurry basin. This practice was extremely cost effective when implemented at a large surface mine, as the need for a 4-foot soil cover was eliminated. However, current or future implementation of this practice is a site-specific choice that requires operational and geochemical analysis to address the economic benefits. The concern expressed by many operators is that in general, slurry dewatering techniques are not cost effective.

Active separation of non-pyritic slurry constituents with mineral processing equipment: Differential separation of slurry constituents using two 24-inch coal preparation classifying cyclones was used (Nawrot et al. 1984) to reduce slurry volume of the classifying cyclone underflow (coarse fraction) reporting to a primary slurry basin. The cyclones generated significant pyrite reduction (~69%) in the slimes content of overflow to allow use of the processed slimes as a wetland soil cover for direct vegetation establishment of a 108-acre slurry basin. Similar to the decant separation (pyrite reduction) practice discussed above, the cyclone pyrite separation alternative also proved to be extremely cost-effective as the need for a 4-foot soil cover was eliminated for more than 93 acres of the 108-acre surface mine slurry basin (Nawrot 1984). Again, the concern expressed by many operators is that in general, slurry dewatering techniques are not cost effective.

To maximize pyrite reduction and enhance the production of a non-acid soil substitute from acid producing slurry, differential separation of non-pyretic slurry constituents from ~10% of preparation plant discharged slurry (without dewatering) may be achieved using specific gravity and size classification mineral processing equipment (hydro-cyclone, classifying cyclone, spiral concentrator) designed in a multi-stage process to initially size classify the more readily recoverable coarse grained calcareous constituents from coarse grained pyretic components prior to gravity separation to eliminate residual pyrite (Fig. 7.5). The non-acid “soil substitute” fraction derived from a portion of the ROM slurry is pumped to cap (upper 4 – 6 foot) the existing slurry basin. The reject (also not dewatered) “non-soil substitute” slurry is returned to the ROM slurry for conventional pumped disposal.
The refinement of the previously documented (Nawrot 1984) and successfully implemented pyrite separation practices can be cost effective alternatives to soil capping existing slurry basins. This is possible when operators include their existing basins in future capping plans by reserving an additional 2-4 foot of freeboard that will be used to “dispose” of the pyrite reduced (non-acid) slurry fraction. When correctly planned and implemented, non-acid slurry processing and capping increases the ultimate storage capacity of existing slurry basins by substituting the upper 4 foot soil cap with a pumped “slurry soil” cap. No additional slurry basins are required to implement this practice as a sequential “slurry soil” capping of the first of a normal series (3 of 4) of traditional slurry basins begins when the ‘reserved” freeboard stage of the first basin is reached. During the disposal of raw slurry in basin 2, “slurry soil” processing is initiated on only a nominal (~10%) portion of the run of mine slurry flow that is needed to satisfy the capping needs of slurry cell 1. Processing of a “slurry soil” and capping is continued only for as long as the need exists to meet a 2 – 4 foot “soil” cover requirement. Operators will be able to assess the efficacy of producing their own soil from the non-pyritic slurry fractions by analyzing site specific operational conditions and the geochemistry of their raw slurry. As run-of-mine Illinois coal basin slurry only contains a maximum 7-8% pyrite (mid range 3-5%), the residual ~90% of raw slurry represents a potential “soil resource”. The same mineral processing equipment that presently recovers desirable high specific gravity constituents such as silver, nickel, gold, etc. performs the same function when employed to reduce or remove a high specific gravity undesirable constituent, pyrite (“fools gold”) from slurry to generate a non-acid soil cover for on-site reclamation needs. Operators will need to review the efficacy of pursuing pyrite reduction practices on a site specific basis.

Figure 7.5. Slurry processing to reduce pyrite and produce a non-acid soil substitute. (Source: Nawrot et al. 1984).
7.5 Water Management

Improved Water Management and Mixing to Achieve Water Quality Standards: Closed-Loop Water Handling Method Permits are designed for no water discharges. Illinois typically has a large excess of rainfall over evaporation. This excess has to be periodically discharged during periods of high precipitation. For example, Carlinville, Illinois annual rainfall is about 35 inches/year and evapo-transpiration is approximately 29.5 inches/year. Therefore, an average surplus of 5.5 inches per year exists. Depending on the annual timing of precipitation, this may or may not result in discharge. Some of this excess moisture leaves the facility as moisture included with the coal product. However, throughout the year there may be periods of intense precipitation that will exceed the mine site’s ability to store water. During these periods of excess rainfall or during periodic discharges (blow down) required to remove accumulated dissolved solids a mixing allowance and compliance reporting may be required. More frequent, lower volume blow-down cycles could be used to minimize mixing requirements. This is especially important where the mine facility is located far from a large stream. In these cases Illinois operators have developed large volume well fields and surface storage facilities to use groundwater as a dilution source. Unlike current practices, separate water handling loops are proposed. One for “fresh” water and one for chloride (where elevated) and/or high sulfate are suggested. The separate clean water loop would serve as a supplemental dilution water source. Blow down from the high sulfate and chloride loops will be controlled and may require use of dilution water from the clean water loop and use of a mixing allowance. Application of existing on-line instrumentation and analysis technology can assist operators with water quality management using this approach.

One important improvement in this PGMP is an added benefit resulting from the application of contemporaneous reclamation. Additional clean water could be derived from re-graded and vegetated mine and refuse areas, mine facilities in which acid-forming materials and chloride sources are covered in a manner that minimizes leaching. This clean water would also be used for preparation plant input water, mine water for dust control, roadway dust control (roadways in the clean-water watershed). As with many existing facilities an external fresh water impoundment source that is derived from surface runoff or ground water may be required to supplement this clean water source. The high sulfate water would include preparation plant and mine discharge runoff from coal waste stockpiles, coal stockpiles, and mine roadways within the high sulfate loop watershed. This area would be minimized by the contemporaneous reclamation PGMPs. This methodology may be especially important where high chloride groundwater is encountered and a separate loop may be needed for the high chloride water.

Design for mixing water requirements is well established by USEPA in a number of documents. The above approach of mixing for chlorides can also be applied to sulfate discharges.
Advantages:

1) Avoids continuous point source discharges and resultant regulatory requirements (reporting, sampling analytical and other regulatory compliance).
2) Retains water for coal mining and processing and refuse transportation.
3) Reduces impact of sulfate and chloride on the streams by dilution.

Disadvantages:

1) Higher water management system complexity.
2) Potentially higher pumping-related and water monitoring costs.
3) Requires increased costs to maintain mixing requirements (i.e. a larger dilution source).
4) Total loading of the stream may not be reduced unless other PGMPs are applied to minimize sulfate and chloride discharges.

Application of Off-site Dilution with a Mixing Allowance:

This is an existing GMP that is applied to mine operations using the closed-loop water handing method. Key features include:
• Permit is designed for no water discharges.
• Although significant amount of water exits the facility as evaporation and moisture on the coal product there is a considerable excess rainfall versus evaporation in Illinois (43 in/yr rainfall vs. 33 in/yr evaporation) and chloride buildup requires “blow-down”
• Where high chloride groundwater is encountered, a separate loop may be needed for the high chloride water.
• Application of mixing may not be feasible where mine facilities are remote from large streams. In this case some operations have used groundwater as a mixing source instead of processing and dilution water. One large, closed underground mine complex in Southwestern Illinois has constructed a long pipeline to carry a high Total Dissolved Solids (TDS) discharge to a mixing zone in a large stream.


“A mixing zone is an area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient water body. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented.”

Note: the water quality criteria must be met at the edge of a mixing zone.
Types of Mixing Zones

Illinois EPA’s mixing zone regulations allow for mixing zone or allowed mixing application on streams where the 7Q10 is greater than zero. If adopted as written, the recently proposed regulations will also allow for mixing on streams where the 7Q1.1 flow is equal to zero. This proposal is aimed at allowing discharges on small streams to use mixing during wet-weather events (when there is flow in both the receiving stream and at the discharge). Illinois EPA provides applicants with procedures for calculation of mixing zone requirements. Figure 7.6 shows an example of a mixing flow chart and notes the definition of the calculation terms. Please note that symbols used here may not be the same as used in IEPA procedures.

Possible GMP improvements are readily available to mine operators by:
• Applying more frequent, lower volume, blow-down cycles that could be used to minimize mixing zone requirements.
• Creating an additional onsite dilution water sources from sediment ponds that collect water from re-vegetated mine and refuse areas and other mine facilities free from acid-forming materials and chloride sources.

An example of a typical application of regulatory mixing in a receiving stream for the purposes of chloride (or sulfate) dilution is shown in Tables 7.2 and 7.3. The following mass balance equation may be used to calculate permit limits protective of water quality standards:

\[ C_E = \frac{C_{OS}(Q_{US} + Q_E) - C_{US}Q_{US}}{Q_E} \]  

(7.1)

Where:
\( C_E \) = allowed effluent concentration
\( C_{OS} \) = water quality standard (in this case for chloride or sulfate)
\( C_{US} \) = background chloride or sulfate concentration in receiving stream
\( Q_{US} \) = upstream flow in receiving stream during discharge
\( Q_E \) = effluent flow
Figure 7.6. Example of a mixing zone: flow chart.

Table 7.2 illustrates the use of the water balance equation to evaluate the needs for the dilution of a hypothetical high chloride discharge with water in the receiving stream. Somewhat reduced reliance on the receiving stream can be achieved by the use of a modified facility water flow handling circuit. This is possible by maximizing the use of on-site water sources to minimize the needs of off-site mixing with external dilution water in the stream (Figure 7.7; Table 7.3).

Table 7.2. Hypothetical mixing application: Dilution by receiving stream with mixing zone only.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Underground</th>
<th>Surface Facility</th>
<th>On-site Source</th>
<th>Mixing</th>
<th>Receiving Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl Concentration</td>
<td>5,000</td>
<td>Cp</td>
<td>300</td>
<td>Cs</td>
<td>10</td>
</tr>
<tr>
<td>Flow</td>
<td>200</td>
<td>Qp</td>
<td>150</td>
<td>Qs</td>
<td>0</td>
</tr>
<tr>
<td>Cl Load*</td>
<td>5,451</td>
<td>Lp</td>
<td>245</td>
<td>Ls</td>
<td>11</td>
</tr>
</tbody>
</table>

C_{rs} = C_{rs} + (Q_{rs} x C_{rs}) + (Q_{rs} x C_{rs})

C_{rs} = 2.980

Let C_{eq} = 1,000 mg/L (Match Values of Red Cells)

Units: Concentration = mg/L, Flow = CFM, and Load = kg/day
* Load calculation (kg/day) = flow (CFM) x 3.785 L/gal x 60 min/hr x 24 hrs/day x contaminant (mg/L) x 1 kg/L = 1,000,000 mg
** Low-Chloride dilution water source form on-site dilution water source (i.e. impoundment or well discharge).
Table 7.3. Hypothetical mixing zone application: Dilution by receiving stream mixing and aided by an on-site fresh water source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Underground</th>
<th>Surface Facility</th>
<th>On-site Source</th>
<th>Mixing</th>
<th>Receiving Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Pump</td>
<td>C_p</td>
<td>Site ID</td>
<td>Runoff Discharge</td>
<td>Site ID</td>
<td>Fresh Water</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Q_fw</td>
</tr>
<tr>
<td>Cl Concentration</td>
<td>5,000</td>
<td></td>
<td>300 C_s</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Flow</td>
<td>200 Q_p</td>
<td></td>
<td>150 Q_s</td>
<td></td>
<td>200 Q_fw</td>
</tr>
<tr>
<td>Cl Load</td>
<td>5,451 L_p</td>
<td></td>
<td>245 L_s</td>
<td></td>
<td>11 L_fw</td>
</tr>
<tr>
<td>C_f-</td>
<td></td>
<td>C_f= (C_f+C_s)</td>
<td></td>
<td>C_f-</td>
<td></td>
</tr>
<tr>
<td>Q_f</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Let C_f=</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,000 mg/L</td>
</tr>
</tbody>
</table>

Units: Concentration = mg/L; Flow = gpm; and Load = kg/day
* Load calculation (kg/day) = flow (gpm) x 3,783 L/gpm x 60 min/hr x 24 hr/day x contaminant (mg/L) x 1 kg/1,000,000 mg.
** Low-Chloride dilution water source form an on-site dilution water source (i.e. impoundment or well discharge).

Figure 7.7. Modified water flow circuit: maximize use of onsite dilution source.
CHAPTER 8
CONCEPTUAL GOOD MANAGEMENT PRACTICES

8.1 Introduction

In this report, the term Conceptual Good Mining Practices (CGMPs) refers to practices that require additional research, technology development and demonstration before they can be implemented by industry. These suggested technologies are based on principles that are acknowledged today as having potential for reducing sulfate and chloride and involve principles of: 1) differential settlement of FCPW, 2) dewatering of slurry with co-disposal and compaction in a coal refuse mono-fill, and 3) contemporaneous cover placement and vegetation. These CGMPs require 1) an understanding of applicable geochemical and physical processes, 2) development of design criteria, 3) demonstration of operational conditions, and 4) evaluation of the economics of the technology. The proposed CGMPs include:

1) Segregated FCPW Disposal.
2) Bulk neutralization co-disposal with alkaline waste material.
3) FCPW Pre-Processing/Conventional Slurry Dewatering
4) Slurry Dewatering with Paste Thickener Technology.

The “Segregated FCPW Disposal” CGMP is a modification of the existing practice in Illinois of a mixed dewatered slurry and CCPW facility. This practice has several key features that will minimize sulfate discharges. The second CGMP is based on the use of alkaline addition to reduce hydraulic conductivity within a CCPW structure to minimize acidification. The third CGMP is fundamentally a new approach because it requires beneficiation of the FCPW discharge from a conventional coal preparation facility. Here conventional dewatering with a belt-type filter press technology is applied only to the coarse FCPW fraction (-100 mesh x 325 mesh). An alternative to this CGMP may use improved paste thickening technology for the entire fraction. CGMPs 1 and 3 above are derivations of slurry management practices presented in Nawrot and Gray (2000). In contrast with co-disposed blended refuse proposed in CGMPs 3 and 4, Segregated Refuse Disposal identifies refuse fractions with a lower potential acidity and places this material in the upper portions of the refuse pile to reduce liming requirements. The material with higher pyrite content is placed lower in the fill below the post-reclamation water table. Three strategies listed below are employed in developing these CGMPs.

8.2 Strategy 1: Prevention by Placement of Sulfate-generating Strata “High and Dry”

This strategy relies on the minimization of oxygen and water from contacting “acid forming material” (AFM) encountered in surface mining or improved refuse disposal area construction by slurry dewatering, and special handing of coal refuse disposal.
The CCPW to FCPW ratio varies from plant to plant but is typically in the range of 1.5 to 2.5 to 1. Three options are proposed for dewatering FCPW containing typically 18% (15-20%) solids. The first two options are intended to dewater FCPW from 18% to +/- 60%. Option 1 employs mechanical means such as a belt-filter press technology to achieve this. In option 2 dewatering is accomplished using natural sedimentation process in specially-constructed drying slurry cells. In both options the dewatered FCPW is transported separate from the CCPW to a load-out bin to avoid FCPW cake breakage due to the moisture adhering to the CCPW (coarse) material. Subsequently, a portion of the FCPW is mixed with the CCPW for subsequent truck disposal in a compacted fill that is smaller in size to conventional structures and is reclaimed in a more contemporaneous manner.

8.3 Strategy 2: Prevention by Placement of Sulfate-generating Strata “Deep and Dark”:

This strategy relies on the minimization of oxygen from contacting AFM in surface mining or refuse disposal by placement of FCPW below the water table. Below the water table the amount of oxygen available for reaction is greatly decreased removing the key requirement for pyrite oxidation. Special handing of overburden and/or coal refuse materials is required in this CGMP. The time of exposure of the AFM is minimized to less than six (6) months. This AFM is placed below the permanent water table either within a surface mine pit or an impoundment. For above ground placement this strategy also includes requirements for contemporaneous grading and reclamation cover material.

8.4 Strategy 3 - Avoidance of Sulfate-Generating Strata during Mining

Additional geologic and geochemical data is especially important in selection of CGMPs that rely on knowledge of the geologic and chemical fabric of the coal deposit such as the characteristics of the rock and floor strata, washability of the coal interval to be mined (not simply engineering data such as percent recovery but also acid-base accounting information on laboratory-scale of washability test fractions). CGMP 5 Segregated Refuse Disposal with Improved Management of Out-of-Seam Dilution addresses the need to identify portions of the coal seam and adjacent strata that could increase sulfate discharges and place this material below the water table to minimize sulfate discharges.

8.5 Conceptual Good Management Practice 1 - Segregated FCPW Disposal: Slurry Partitioning, Dewatering by Decantation in Impoundments, Co-disposal with Coarse Coal Refuse, and Contemporaneous Reclamation

This CGMP uses natural classification of particles or zonation within an open water body that results from gravity and particle characteristics. Nawrot and Gray (2000) illustrated the changes in important physical and chemical properties of these zones (Figure 8.1) when discharged from a single point into impoundments with a suitable depth and detention time. In some cases surface mine last cut and haul ramp
impoundments have been employed (Figure 8.2). Note, however, that in the conventional slurry placement the discharge location is fixed and lies above the mean water table and the capillary fringe (top of Figure 8.2). This exposes material with the highest acid-forming potential to oxidation. In the proposed CGMP two options for controlled segregation of the slurry are considered: Option 1 - the slurry is released from a non-scouring discharge directly into the impounded water (Figure 8.3), and Option 2 – the slurry is discharged onto a moderately sloping (+/- 12%) bank of a slurry cell (Figure 8.4). The slope of this discharge zone may have to be adjusted to prevent scouring of the materials high in pyrite that are being concentrated in the discharge zone. In both options conventional pumped thickener underflow slurry (18% solids) is released from a non-scouring discharge structure such as a weir manifold. Separation occurs by particle size and density and depending upon the flow velocity and detention time associated with Stokes Law the dense, more acidic, pyrite-bearing particles will settle in the Discharge Zone and to a lesser extent the Intermediate Zone (which also has some contained calcite); nutrient-bearing (if scouring in the discharge zone the resultant remobilization of pyrites is prevented), low-acid potential particles will concentrate in the more distant Impounded Zone (Figure 8.1 and Tables 8.1 and 8.2; Nawrot and Gray, 2000).

Figure 8.1. Physical and geochemical characteristics of typical slurry zones (Source: Nawrot and Gray, 2000).
Table 8.1. Physico-chemical properties associated with differential distribution of slurry components based on distance from the discharge point.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distance from discharge (m) in a 1,000m long basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - &lt;90</td>
</tr>
<tr>
<td>Texture</td>
<td></td>
</tr>
<tr>
<td>% Sand</td>
<td>70.4 (2)</td>
</tr>
<tr>
<td>% Silt</td>
<td>16.4 (2)</td>
</tr>
<tr>
<td>% Clay</td>
<td>13.3 (2)</td>
</tr>
<tr>
<td>Acidity</td>
<td></td>
</tr>
<tr>
<td>Potential Acidity</td>
<td>416.9 (9)</td>
</tr>
<tr>
<td>(T CaCO₃ equiv. ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>neutralization</td>
<td>385.3 (4)</td>
</tr>
<tr>
<td>potential</td>
<td>± 200 (4)</td>
</tr>
<tr>
<td>Total Sulfur (%)</td>
<td>8.1 (4)</td>
</tr>
<tr>
<td>Macronutrients</td>
<td></td>
</tr>
<tr>
<td>P₁ (Weak Bray, ppm)</td>
<td>4.6 (9)</td>
</tr>
<tr>
<td>P₂ (Strong Bray, ppm)</td>
<td>21.0 (9)</td>
</tr>
<tr>
<td>K (ppm)</td>
<td>64.0 (9)</td>
</tr>
</tbody>
</table>


Table 8.2. Acid balance resulting from segregated disposal in Southern Illinois.

<table>
<thead>
<tr>
<th>Location</th>
<th>pH</th>
<th>Potential Acidity (Tons CaCO₃ eq. Ha⁻¹)</th>
<th>Neutralization Potential (Tons CaCO₃ eq. Ha⁻¹)</th>
<th>Net Neutralization Potential (Tons CaCO₃ eq. Ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid-Containment Cell: Cell A (6 Ha) (n=10)</td>
<td>7.3</td>
<td>115.8</td>
<td>97.2</td>
<td>(-)18.6</td>
</tr>
<tr>
<td>Acid-Containment Cell: Cell B (3.6 Ha) (n=10)</td>
<td>7.4</td>
<td>327.0</td>
<td>23.2</td>
<td>(-92.3)</td>
</tr>
<tr>
<td>Silt-Clay Settling Cell: Cell C (13.4 Ha) (n=11)</td>
<td>7.8</td>
<td>35.2</td>
<td>67.7</td>
<td>32.7</td>
</tr>
</tbody>
</table>

Source: Nawrot and Gray (2000); samples were collected from the surface 15 cm; the high neutralization potential in the discharge zone is due to the presence of calcite.

In this proposed practice multiple slurry cells are needed for the sequence of placement, dewatering by decantation and recovery of coarse FCPW from the discharge zone and, if desirable, the clay-rich, nutrient-bearing fine material (< 325 mesh) from the impoundment (Figure 8.3, Clay Deposit zone). The decantation process would be designed to remove water from the discharge zone and an under-drain system may be required to adequately lower the moisture content. It is
proposed that the dewatered slurry would, subsequently, be recovered by towed scrapers typically used for wetland construction. A comparison of the technical viability and economics of this slurry re-handing compared to the environmental benefits would have to be evaluated.

Conversely, clay-rich fines could be recovered by use of a floating cutter-head dredge since this would allow placement of the clay cap by low-cost pumping (Figure 8.3). In cases where the clay cap material is net acid-forming, a relatively small amount of alkaline addition may be required to the air-dried cap.

![Figure 8.2](image.png)

Figure 8.2. Example of natural slurry zones within a final cut impoundment (source: Nawrot and Gray, 2000).
As illustrated by Figures 8.3 and 8.4, slurry impoundment in facilities similar to existing facilities is proposed. The facility is incised in an area of level terrain down to a +/- 10-foot depth. Topsoil and subsoil from the area are initially stockpiled for final reclamation with the additional earth used to build an initial containment levee and several internal partitions to create three cells. To limit acidification of the slurry and associated sulfate discharges, all refuse with acid-producing potential is inundated during placement. Exposure above the water level and capillary fringe in an unsaturated condition should be restricted to less than six (6) months for dewatering, placement on the CCPW facility, and exposure before reclamation.

Figure 8.3. Engineered slurry zones within a proposed improved slurry impoundment structure: option 1.
Figure 8.4. Engineered slurry zones within proposed improved slurry impoundment: option 2.
As the structure increases in height the levee and internal, earthen partitions are constructed and lined with non-acid-forming, clay-rich materials derived from the FCPW. Due to the existence of multiple cells and removal of Discharge and Impounded (Clay Deposit) zones, the storage needs of these cells are significantly reduced and, therefore, a dewatered impoundment will result. The cutter-head dredge can also be used to level Intermediate zone deposits by placement into deep water areas created by the clay-rich fraction excavation. One option could be to reverse the system flow following coarse FCPW and clay recovery and then a new Clay Deposit zone forms over the former Discharge zone, effectively encapsulating remaining pyrite-bearing material (Figures 8.3, 8.5).

An alternate geometry for development of this concept is shown in Figure 8.4. In Option 2 the slurry is discharged from a weir manifold onto a moderately sloping (+/-12%) bank of a slurry cell. Otherwise, the operation is similar to that described for Option 1. Additional studies are needed to evaluate system placement geometry, decantation methods and sequencing of the coarse FCPW and clay deposit material. In practice the operation of this type of management practice would require a high degree of supervision. Final reclamation could include either creation of permanent water and wetland or construction of a permanent reclamation cover whichever land use is appropriate for the site (Figure 8.5).

<table>
<thead>
<tr>
<th>Acid Forming Potential (Net Neutralization Potential)</th>
<th>Placement Sequence</th>
<th>Hydrologic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Cover material (2-4 ft.) over lime-amended clay*</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low/none</td>
<td>Decanted clay fraction 1/4 Slurry</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>Decanted highly-pyritic fraction 1/4 Slurry</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low/none</td>
<td>Decanted clay fraction 1/4 Slurry</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>Decanted highly-pyritic fraction 1/4 Slurry</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low/none</td>
<td>Decanted clay fraction 1/4 Slurry</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>Decanted highly-pyritic fraction 1/4 Slurry</td>
<td>Moderate</td>
</tr>
<tr>
<td>(Sequence repeats to bottom of cell)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Lime amendment of top surface as needed based on soil tests.

Figure 8.5. Sequence of encapsulated pyrite-bearing refuse and clay-rich cover material resulting from the segregated disposal good management practice

**Improvements from Proposed GMP Application**

1) Eliminates liabilities associated with large elevated slurry impoundments.
2) Coarse FCPW will be available for improved CCPW facility construction.
3) Clay-rich material with lower potential acidity is available for construction of an improved final cover material for CCPW facility (Note: After separation this material may still be classified as AFM and in this case lime addition will be required).

4) Permanent water cover and wetland reclamation eliminate the cost of liming (70-80 tons/acre) the top one-foot of FCPW and covering the structure with 4-feet of non-acid forming materials (Nawrot, 1986).

5) Embankments are constructed of desirable earth materials in compacted lifts that are structurally much more stable than embankments constructed of CCPW.

6) If smaller micro-cells (<2.0-acre) are constructed, these will not require MSHA approval.

7) Micro-cells can be sequentially released reducing bonding requirements and developmental liabilities.

8) Runoff from reclaimed areas can be used for on-site dilution of high sulfate and/or chloride discharges from active coal mining and processing areas.

Disadvantages of this CGMP Application

1) Earthen cell construction requires bank material excavation that is higher cost than CCPW currently utilized.

2) A separate storage area is required for CCPW.

3) Rehandling FCPW materials requires added equipment and costs.

4) Periodic movement of FCPW discharge location requires additional labor and pipeline material costs.

8.6 Conceptual Good Management Practice 2 - Slurry Classification and Mechanical Dewatering: Slurry Partitioning, Dewatering of Coarse Slurry Fraction, Co-disposal with Coarse Coal Refuse, and Contemporaneous Cover Placement

With this CGMP slurry or FCPW is partitioned to separate the very fine particles smaller than 325 mesh (45 micrometer) fraction and a coarser, 100 x 325 mesh (150 x 45 micrometer) fractions. This separation, with a classifying cyclone (Figure 8.6), removes fine, clay-rich portion, which is very difficult to dewater. The coarser fraction is, subsequently, dewatered from +/- 18% solids content to approximately 60-65% solids content using advanced filtration technology such as belt-type filter press or possibly an improved screen bowl centrifuge. The dewatered FCPW (filter cake where a filter press is used) is carried by a conveyor belt to a load-out bin from where it is hauled with the coarse and middling fractions of the refuse by truck or, preferably, by either a scraper or an ejector-type articulated dump truck (ADT) to the stockpile. The combined CCPW or coarse and FCPW facility (Figures 8.7a and 8.7b) is constructed of a blend of CCPW (jig or heavy-media reject (typically 34% of the total refuse fraction by weight), middling fraction material (small diameter cyclone and/or spiral reject; about 37% of the total), and the dewatered, 100 x 325 mesh, FCPW from the classifying cyclone (about 14% of the total refuse, Figure 8.6). The dewatered (60% + solids) FCPW at a 1:5 FCPW to CCPW ratio is added in the CCPW load-out bin and is placed in thin lifts by a scraper or ADT to form dome-
shaped stockpile. The use of scrapers or an ejector-type ADT (Figure 8.8) is suggested to improve compaction, reduce refuse haul cycle times and the need for using a dozer to spread truck-dumped materials. Improvement in compaction of outer slopes where compaction by haul vehicle traffic is not possible is also desired. Steep slope compaction is possible with the use of padded foot-type compactors such as the tracked, self propelled Sakai CV550T (maximum 1:1 slopes, Figure 8.9) or the more conventional Caterpillar 824G (maximum 2:1 slopes). The dewatering improves the stability of the pile which is also enhanced by systematic compaction, partially incising the structure below the natural ground level and constructing a strong earthen embankment buttress around the refuse pile perimeter (Figure 8.7a). The depth of the excavated cut is relatively shallow, but is sufficient to allow removal of topsoil and subsoil for the 4-foot thick reclamation cover for the gob pile perimeter embankment and construction-fill embankment throughout the facility. A key design feature of this CGMP is that unlike typical Illinois structures, the gob pile is not constructed from the bottom up and inside out, but is built from one end of the facility to the other. This allows for contemporaneous reclamation following alkaline amendment of the final graded and compacted slopes, and covering with at least 2-foot of a non-acid and non-toxic forming cover.

Figure 8.6. Modified coal processing for production of combined course and dewatered FCPW materials.
Figure 8.7a. Range diagram for contemporaneous placement of combined coarse and dewatered FCPW materials.

Figure 8.7b: Improved coal refuse facility with combined coarse and dewatered FCPW materials and managed slurry impoundments.
Figure 8.8. Typical 40-ton class articulated dump truck with an ejector bed.

Figure 8.9. Typical steep-slope compactor (smooth drum version shown).
To minimize acidification of the refuse during the disposal process, the refuse should be compacted and covered in a timely manner. The period of refuse exposure can be determined on a site-specific basis by cost effective, empirical sampling of refuse collected in field conditions. Static and kinetic tests (i.e. column leaching studies) of reject (sink fraction) materials obtained from washability studies may be applicable based on extensive verification with refuse collected in field conditions. Previous assessment and analyses of various age refuse (0 to 2 months to > 24 months) and refuse from various refuse disposal facilities (Nawrot, 2006 personal communication) have documented that the critical exposure period is 3 to 6 months. Note that there are other seasonal climatic factors (i.e. temperature and amount of precipitation) that will impact the duration of the critical exposure period.

Co-placement allows for increased compaction and reduction of the hydraulic conductivity for CCPW, and the FCPW exhibits the least acid-forming potential (highest NNP) and the lowest hydraulic conductivity after placement. In this process deep weathering of the gob pile is reduced with reduction in sulfate generation. The remaining clay-rich slurry (14% of the refuse total) is placed in a separate slurry impoundment. Because of the separation of the coarser faction of the FCPW the external slurry impoundment can be considerably smaller than conventional cells. This clay-rich material can be dewatered by decanting and air drying if placed in thin lifts (0.25-foot thick). Multiple ponds are required to allow sequencing of the dewatering process with the decant water being collected in a central impoundment (Figure 8.7b; Note: the decantation process described here may be ineffective during periods of extended precipitation). Nawrot and Warburton (1987) report that most Midwest coal slurry is non-acid during active disposal and remains non-acid for between 14 to 18 months following inactivation and dewatering, but that acidification will begin after drawdown and dewatering when pyritic sulfur in the slurry (typically 1 - 5%) is exposed to sub-aerial weathering and begins to oxidize. Therefore, the dewatered, clay-rich slurry should be sequentially covered with fresh slurry or excavated and placed within the CCPW structural fill (where dewatering is sufficient for geotechnical stability of the pile).

Improvements from Proposed CGMP Application

1) Incorporates systematic contemporaneous reclamation. The cover material is placed as a more-or-less continuous sequential operation allowing early release of bond funds and reclamation liabilities. Most of the reclamation cover can be placed directly after excavation thereby eliminating the footprint areas of cover material stockpiles and costs associated with rehandling of this material.

2) Improves compaction of refuse that is directly related to decrease in hydraulic conductivity of the structural fill for improved AMD prevention. Therefore, sulfate discharge and operational period water treatment costs are reduced.

3) Improves waste material handling efficiency by increasing fill factor, decreasing cycle times, and eliminating the need for a full time use of a dozer and sheep-foot roller to spread and compact the end-dumped refuse.
4) Increases the geotechnical stability of the refuse pile, thereby reducing project developmental liability.

5) Where refuse pile is incised a portion of the refuse with the highest acid-forming potential (as determined by mine planning and analysis) can be located below a perched, shallow ground water table (the dark and deep scenario).

6) Where the clay-rich FCPW portion possesses a suitable ABA, this material can be excavated from the managed slurry cells and used for impervious barrier and subsoil substitute in an engineered-type cover.

Disadvantages of the Proposed CGMP Application

1) Additional costs for processing and dewatering of FCPW.
2) Additional costs for truck haulage of dewatered fines compared to pumping.
3) Future recovery of carbon value in 100 x 325 mesh fraction is eliminated.
4) Additional costs for construction of separate slurry ponds.
5) Management requirements are greater than current practice.

8.7 Conceptual Good Management Practice 3: Bulk Neutralization by Co-disposal with Alkaline Waste Material

The goal for the proposed alkaline addition strategy is to improve ABA and offset the acid-generating potential. Due to the high potential acidity and low neutralization potential of coal refuse in Illinois a large amount of alkaline addition would be required for bulk neutralization of these materials. Because of the high cost associated with bulk neutralization, this would most likely require application of other CGMPs unless the refuse facility is located adjacent to a large source of alkaline waste materials such as cogeneration plant equipped with a fluidized-bed combustion (FBC) boiler (FBC ash used for alkaline addition), or cement or lime manufacturing plants for lime kiln dust or cement kiln dust. Application of agricultural limestone on the surface of coal refuse prior to cover replacement (or in lieu of cover replacement in weathered abandoned site) is a standard practice (Nawrot et al, 1986). However, bulk additions of alkaline waste materials such as cement kiln dust (CKD) and coal combustion byproducts (CCBs) have been used in Pennsylvania, West Virginia and Kentucky to minimize the acid-generating potential of coal refuse. Stewart et al. (1997) report that the co-disposal of alkaline byproducts and coal refuse is common in other countries (Skarzynska, 1995; Twardowska, 1990). A number of Illinois coal refuse disposal facilities are favorably located to alkaline source materials that co-disposal is a viable option. In such cases AMD (sulfate generation) is prevented and beneficial use of CCBs is an integral part of the refuse management facility. Stewart et al. (2001, 1997) and Stewart and Daniels (1996) studied a series of blends of low-calcium carbonate equivalent (CCE) Type F ash (5-11% CCE) derived from combustion of Appalachian coals, and moderately high potential acidity refuse (130 T CCE/1,000 tons of material). The research of Stewart and others (Stewart et al., 2001, 1997; Stewart and Daniels, 1996) used column leach studies to show that bulk alkaline addition rates of only 20 to 33 percent were required to prevent acidification of the refuse (Figure 8.10). However, it should be noted that these leach studies were
relatively short term (< 3 years) and therefore long-term success is not proven. As previously mentioned kinetic test standardization and scale-up factors limit the application of this approach at this time. Dreher et al. (1994, 1996) used mixtures of fluidized bed combustion (FBC) with FCPW materials derived from Illinois. The amount of FBC material added (about 10%) was sufficient to neutralize the acid-forming potential of the FCPW. Considerable sulfate was generated in leaching studies by Dreher et al. (1994, 1996) that were attributed in part to the mobilization of sulfate in anhydrite, a form of gypsum common in FBC ash.

FBC fly ash may also be added to the CCPW to improve ABA and cement it to reduce its permeability and improve its geotechnical performance. One moderate-sized underground mine in central Illinois currently employs this strategy of mixing about 22% of FBC ash to the CCPW to construct refuse embankments. Sulfate was also elevated in leachate tests in surface treatment mixtures of flue gas desulfurization (FGD) wet scrubber sludge and coal refuse (Mafi, 1997). Wet FGD material has low NNP and it is also high in sulfate (gypsum).

Figure 8.10. Examples of kinetic leach test cells for mine waste studies (source: Lawrence, 1995).

**Improvements from the Proposed CGMP Application**

1) Alkaline additions are capable of converting the refuse from AFM to non-AFM.
2) Waste materials are readily available at some sites (i.e. mine-mouth power plants, mines with truck haulage to the industrial and utility consumer and haul-back arrangements for alkaline wastes (CCBs such as FBC ash or CKD or LKD).
3) Alkaline material can also be used at the site for beneficial uses in civil-engineering applications such as haul road construction, soil stabilization, and as soil amendments.

Disadvantages with the Proposed CGMP Application:

1) SMCRA prohibits placement of solid waste in CCPW (coal refuse) and CCBs are by definition a solid waste. Therefore, additions of CCBs to CCPW must be for approved beneficial uses. Neutralization of acid-forming material can be considered a beneficial use if it is demonstrated that net alkaline conditions will persist and leaching of trace elements will not impact the hydrologic environment.

2) Increases permitting, monitoring, and reporting costs associated with CCB beneficial use.

8.8 Conceptual Good Management Practice 4: Slurry Dewatering with Paste Thickener Technology, Co-disposal with Modified Coarse Coal Refuse, and Contemporaneous Cover Placement

Modified and environment friendly CCPW can be the result of an additional CGMP whose goal is to produce refuse materials with improved geotechnical properties. This material should allow increased compaction and bearing capacity. Such material will possess a lower hydraulic conductivity to reduce infiltration of water and oxygen. When placed and compacted in a timely manner this material should minimize formation of acid mine drainage (AMD) and the resulting discharge of sulfate and ferric iron. Ferric iron is a powerful oxidant and is capable of weathering pyrite contained within a slurry cell even when the material is placed in a low oxygen environment under the impounded water.

Modified CCPW is developed by screening the jig or heavy-media reject portion of the CCPW and then crushing the overflow material. The resulting crushed refuse can either be rerouted through the processing plant if there is sufficient coal which can be recovered or directly blended with the scalping screen underflow and the spiral reject portions. In addition about 10 percent dewatered (60-65 percent solids content) FCPW is added to improve the geotechnical properties of the resultant mix. In this CGMP dewatering is accomplished by a paste thickener technology (Figure 8.11). Paste or deep cone thickeners are not a new technology and are gaining wide acceptance in the hard rock mineral processing sector. This technology is advocated as a measure to reduce the environmental risks associated with large metal mine tailings and coal slurry impoundments (Parekh et al., 2005; National Research Council, 2002). Recent bench and pilot scale processing with bituminous coal mine FCPW in West Virginia has shown encouraging results compared to filter cake from belt-pressed material from the same mine (Table 8.3; Figure 8.12). However, currently no paste-thickners are in use in coal industry in the USA.
Table 8.3. Results of pilots scale testing of coal slurry by Parekh et al. (2005).

<table>
<thead>
<tr>
<th>Past Thickener Bed Height (feet)</th>
<th>Percent Solids in Underflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>51.5</td>
</tr>
<tr>
<td>10</td>
<td>52.9</td>
</tr>
<tr>
<td>11</td>
<td>52.7</td>
</tr>
<tr>
<td>Existing Filter Press Cake</td>
<td>52.5</td>
</tr>
<tr>
<td>8*</td>
<td>70.0</td>
</tr>
</tbody>
</table>

* Feed = Drain slurry from a screen bowl centrifuge

In the pilot tests by Parekh et al. (2005) both cationic and anionic polymers were added to the underflow from a conventional thickener and fed into a deep cone paste thickener (Figure 8.11). The FCPW paste can then be pumped either directly to the refuse pile and spread as thin lifts or dumped onto a conveyor and transported to the CCPW (refuse) load-out bin (Figure 8.11 and 8.12).

Figure 8.11. Diagram of a typical deep cone thickener (Parekh et al., 2005); thickener underflow = feed.

Pilot tests by Parekh et al. (2005) were unable to achieve the design solids content of at least 60 percent. However, the results were comparable to a filter press product (Table 8.3). A higher percent solids content (70%) was achieved when the paste thickener was applied to the partially-dewatered waste drained from a screen bowl centrifuge (Table 8.3). The construction of the combined CCPW and FCPW structural fill is consistent with that proposed in CGMP 2. The use of scrapers or an ejector-type ADT (Figure 8.8) is suggested to improve compaction, reduce refuse haul cycle times and the need for using a dozer to spread truck-dumped materials.
Improvement in compaction of outer slopes where compaction by haul vehicle traffic is not possible is again desired.

**Improvements from Proposed CGMP Application**

1) Elimination of slurry impoundment reduces risk associated with coal refuse disposal.
2) Reduces potential for sulfate discharges (as well as AMD).
3) Reduces footprint of coal refuse facility.
4) May allow increase in coal preparation throughput capacity by easing waste disposal needs.
5) Increases amount of return water thereby reducing need for makeup water from surface water and groundwater sources.
6) Fill factor is increased for haul trucks.

**Disadvantages of the Proposed CGMP Application:**

1) Additional processing equipment increases capital and operating costs of waste processing.
2) Requirement to add flocculent significantly increases dewatering cost.
3) Stability of the structure must be considered if all of the slurry is dewatered (dewatered FCPW = 29% versus 14%); layering of pumped paste could reduce these concerns (Parekh et al., 2005).
Figure 8.12. Deep cone thickener setup with addition of paste thickening as suggested by Parekh et al. (2005).
8.9 Conceptual Good Management Practice 5 – Identify Problematic Strata for Selective Out-of-Seam Dilution

This GMP identifies problematic strata associated with the coal seam and minimizes its mining to the extent possible. This GMP would require improvements in the pre-mining investigations phase to better characterize the out-of-seam materials (immediate roof and floor strata) from ABA point of view. Using these data operators can develop a mining plan and coal refuse disposal plan considering operational factors such as mining height and roof and floor control. Armed with this geochemical information mine operators can develop a special material handling plan that places material with lower acid-forming potential above material with lower acid forming potential. An example is shown in Figure 8.13 where dewatered slurry (FCPW) and middling material is co-disposed in a separate lift above CCPW with a higher acid-forming potential. In this case the material with higher acid-forming potential, usually the jig or heavy-media reject refuse is placed lower in the mine refuse pile below the final reclamation water table, otherwise known as the “deep and dark” reclamation strategy, thereby reducing the acidification of the CCPW.

![Segregated Refuse Option: Dewatered Slurry + Midlings over Coarse Refuse](image)

Figure 8.13. Segregated refuse CGMP option.

As illustrated in Figure 813 due to relatively high amount of jig reject in the refuse pile (~34% of the total coal refuse), incising the structure would be useful from a geochemical standpoint with additional geotechnical advantages. In this case the middling material (~37% of the total coal refuse) is blended with dewatered FCPW (~29% of the total refuse) and placed over the jig or heavy media reject portion of the CCPW. The processing flow chart for this option is similar to the processing steps shown in Figure 8.6 or Figure 8.12) except that the jig reject is placed in a separate load-out bin hauled to the lower part of the refuse structure.

Improvements from the Proposed CGMP Application

1) Sulfate discharges are reduced from processing and refuse facilities because contaminant (pyritic sulfur) is left underground in predominantly undisturbed state and in an anoxic environment.

2) Where floor material is non-sulfate-generating and can be economically removed to obtain additional mining height, removal of floor material may be advantageous over removal of an acid-forming roof material.

3) Possible improved roof stability if roof material is non-sulfate- and/or chloride-generating and competent and is removed to obtain additional mining height.
4) Where the segregated refuse disposal option is selected, the elimination of slurry impoundment reduces risk associated with coal refuse disposal.
5) Segregated refuse disposal reduces potential for sulfate discharges (as well as AMD).
6) Dewatering of FCPW increases amount of return water thereby reducing need for makeup water from surface water and groundwater.

Disadvantages of the Proposed CGMP Application

1) Immediate weak roof rock (typically high in pyrite) may require mining for roof control and miner safety.
2) There may be technological, industrial health, and economic limitations in deciding to cut hard floor and roof strata. For example, cutting of a sandstone roof rock material may lead to increased equipment maintenance and the generation of silica-bearing dust (an industrial hazard).
3) Production of additional clay-rich material in refuse from mining floor underclay materials can result in excessive coal processing costs.
4) Higher geologic and environmental data acquisition and permit preparation costs.
5) Additional processing equipment increases capital and operating costs of waste processing for the segregated refuse option.
6) Stability of the structure must be considered because all of the slurry is dewatered (dewatered FCPW = 29% versus 14%). Layering of pumped paste could be considered to reduce these concerns Parekh et al. (2005).

8.10 Assess potential of the new Acid Drainage Technology Initiative (ADTI) kinetic (column) leach test to predict sulfate/chloride-forming potential:

One of the goals of this study was to identify a predictive tool to assess potential for sulfate and chloride discharges during pre-mining investigations. ADTI kinetic leach test using sink fraction of coal cores from washability studies and planned out-of-seam dilution from roof and floor strata may provide data to achieve this goal. By use of a standardized test variability in kinetic testing can be eliminated. Verification and development of scale-up factor/s can be accomplished by comparisons of the standard lab kinetic tests to larger-scale field kinetic tests.

The CGMPs described above have been briefly discussed with several mine operators and among the project team members. There is general consensus that additional work is necessary to identify some of these that would be worthy of field demonstration on pilot scale and/or field scale.
CHAPTER 9
DEVELOPMENT OF A DEVICE FOR ASSESSING FIELD COMPACTION

9.1 Background and Problem

It is a well established fact that compaction of coal processing waste achieves the twin objectives of increased structural safety and decreased acidification/leaching potential of the refuse piles (Stewart, 2004). Proper compaction of the coal refuse delays the influx of air/water by lowering the permeability and hence, acts as a retardant to sulfate/chloride generation. However, at times it becomes impractical for coal mine operators to achieve proper compaction at every location on the refuse pile.

For example, federal and state laws require refuse to be compacted and disposal sites to be inspected. However, there is no simple technique or instrumentation available that can accurately measure or assess the state of compaction in different areas of a coal refuse pile from air and water percolation points of view. ASTM standard double-ring infiltrometer test (ASTM2003) is available but it is cumbersome and time consuming. Current evaluation of compaction is often conducted with the aid of nuclear moisture gage. This industry accepted method provides accurate results. However, it does not provide information on air and water percolation rates.

According to industry professionals interview during this study, other density measurement techniques are available; but most are expensive, bulky, or require a great deal of time, and most do not return consistent results over the wide range of refuse materials. Attempts were therefore undertaken to create a simple method for quick evaluation of refuse compaction that would indicate relative potential for air and water percolation through refuse at a particular site. The need for a simple tool to give a relative comparison of compaction, especially in less compacted areas near the edges of lifts constructing steep slopes was considered important. This specific need was addressed in the development below. The concept of development is similar to ASTM double-ring infiltrometer but it is simple and develops relative compaction index in different areas of a particular site based on materials collected at that site.

Field observations made by professionals interviewed during this study suggested that the interior or bulk of refuse piles stay well compacted and structurally sound. But the compaction varied widely with the nature of the refuse, the methods of compaction, and the degree to which material near the edge of lifts was compacted. The outer edge of each lift eventually forms the surface upon which final cover will be placed. Typically, the side slopes of the refuse piles remain largely un-compacted even if compaction equipment is used in remainder of the refuse pile. Neither haul-trucks nor dozers can access this section of a refuse pile properly because of tipping hazards. At the same time, this is the zone in a refuse pile that is more prone to weathering, acidification and sulfate/chloride generation since compaction is poor. Coal refuse is also known to self-compact (Stewart, 2004) after it has undergone weathering to some extent. However, by this time acidification of refuse may have initiated turning the pile into a sulfate-generating source. All of the above reasons make compaction a critical process for any sulfate/chloride minimization plan.
9.2 Hypotheses for a Simplified Approach to Compaction Assessment

Water infiltration rates through cohesive soil-type materials are related to the degree to compaction. It was hypothesized that the time required for a given amount of water to pass through a known volume of refuse, at known degrees of compaction should therefore be correlated. To test this hypothesis, both laboratory and field investigations were planned. As part of the laboratory investigation, coarse coal refuse was collected and compacted with variable compaction effort. Water was allowed to percolate through columns of compacted coarse refuse, noting the percolation time. Then, graphs were plotted for percolation time vs. compaction effort. Eventually, it was planned to perform field percolation test with a similar device and compare the time taken for the percolation in the field with the laboratory results to get an idea of the field compaction. The laboratory and field investigations were planned to be performed on the refuse from the same mine.

9.3 Laboratory Studies and Results

Fresh refuse grab samples were collected from an operating Illinois coal mine end-dumped, relatively fresh refuse pile. The samples were tested for moisture, and particles larger than three inches in any linear dimension were eliminated. A 6 inch diameter x 7 inch long cylindrical compaction mold was filled in three layers, with each layer compacted with a standard proctor compaction hammer, imparting 25 blows per layer. Each mold was then fitted with a clear graduated cylinder, at the top (Figure 9.1). A perforated 1/8\textsuperscript{th} inch disk of gasket material was placed on top of the sample to allow influx of water only through the compacted refuse. Known volumes of water were then introduced at the top of each cylinder, using a transparent container. Time and volume of water percolating through the refuse column was recorded. This experiment was carried out for refuse compacted with variable compaction efforts.

Figure 9.1. Laboratory version of the developed percolation device
Volume of water that percolated through the compacted refuse and time of percolation are plotted in Figure 9.2, along with the relative compaction effort (100% being standard compaction effort). The figure clearly suggests that a correlation exists between compaction effort put into densification of the refuse and the rate of percolation through the refuse column, as was hypothesized.

![Figure 9.2. Volume of percolation vs. time (at varying compaction efforts).](image)

Another set of tests were conducted at lower degrees of compaction, as the coal refuse piles are never compacted to the density achieved during standard Proctor test. In this round of tests, single layers of refuse weighing ten pounds each were compacted in the same molds. The refuse was compacted in a single lift to simulate the field conditions, where lift thicknesses run between 1-2 feet. Compaction was achieved by the standard Proctor hammer, but delivered through a 1/8\textsuperscript{th} inch by 5 and 3/4 inch diameter plate placed on top of the refuse. Compaction efforts were varied and percolation tests were run at 5, 10, 15, 20 and 25 blows for the entire test column; 25 blow being equivalent to 100% compaction effort. This range of compaction more closely resembled conditions found at the lift edges of the refuse pile. The depth of each compacted sample was plotted. A known volume of water (3,000 ml) was introduced into each cylinder and the time for the first 1,000 ml to enter the sample was plotted. Only the infiltration of the first 1,000 ml water was studied, as in the field conditions also the initial flux of water is the most damaging from a leaching point of view. The results are presented in Figure 9.3. Again, a definite correlation is observed between the percentage of standard compaction and time of water percolation through the refuse column. Also, it was observed that the height of compacted refuse column steadily decreased with increased compaction, which was
expected. Encouraged by the results indicating direct correlation between the compaction effort and water percolation rate, plans were made to develop a field device using percolation as an indicator of relative compaction in near homogeneous refuse.

Figure 9.3. Rate of percolation and sample height vs. compaction effort.

9.4 Design of Field Equipment

The field equipment uses common ABS pipe (6 in diameter) cut to 8 inch lengths and beveled at the bottom (Figure 9.4). Clear 1 gallon plastic wide mouth bottles with the bottom cut out were marked at 100 ml intervals and fitted to the pipe with a rubber seal and hose clamps. The low cost of this assembly allowed multiple devices to be made. This allowed more than one test to be performed at the same time and if damaged, parts could be replaced with parts kept on hand. The bottom section was also fabricated using 6-inch diameter carbon steel tubing for use in areas of high compaction. The use of light components for construction of this device made it easy to carry and maneuver in the field.
While using the field compaction assessment device, an oak header board was placed over the top of the drivable bottom section then a pipe with a 6 inch flat plate welded to the bottom was used to drive the section into the refuse down to a depth of 6 inches. A perforated diffuser was then placed over the refuse. The seal and cylinder were then fitted to the lower section. Three liters of water were then introduced and volumes timed while percolating through the cylinder. Bench scale tests were conducted to debug the process. The device was driven into compacted refuse contained in buckets. The device drove well in all but highly compacted refuse. With effort the steel version could be driven into and removed from highly compacted refuse. A small number of individual tests had to be repeated when a large chunk was encountered. Small leaks were avoided by the use of a small amount of sealant applied to the rubber gasket.

9.5 Field Studies and Results

The time demands for other tasks of the sulfates and chlorides project limited the opportunity for extensive testing using the device. Unfortunately, field studies could not be carried out for the mine site, whose coarse refuse was used for the laboratory investigations of this approach. Preliminary tests were conducted during visits to two (2) different mine refuse sites, to perfect the technique. Finally, the device was used to characterize the compaction of a refuse pile at one specific mine site. The results are presented in Table 9.1. The time required for a given volume of water changed dramatically as testing progressed from areas of loose fresh refuse to areas (3 feet from edge of lift and no equipment travel) to lightly compacted areas (tractor treads single pass) to more compacted areas (tractor treads 8-12 passes) to compacted areas...
(haul truck delivery road) to heavily compacted areas (main haul truck access to top lift from ramp). The results in the heavily compacted areas showed less than 250 ml entering the refuse in 30 minutes (the rate slowed over time). The loose areas typically showed 3,000 ml percolating the refuse in less than 1 minute with the first 1,000 ml entering at the rate of pour.

Table 9.1. Results of field compaction assessment

<table>
<thead>
<tr>
<th>Distance from Edge of Refuse Pile (feet)</th>
<th>Volume of Percolated Water (ml.)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3000</td>
<td>0:49</td>
</tr>
<tr>
<td>6</td>
<td>2500</td>
<td>7:00</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>25:00</td>
</tr>
</tbody>
</table>

9.6 Discussion and Opinion

The technique outlined in this chapter provides an easy approach too qualitatively and may be even quantitatively characterize relative compaction at different locations in a coal refuse pile. The limited results obtained during this study indicate correlation between compaction effort and rate of water percolation, as would be intuitively expected. However, the methods and concepts used in this effort are still at developmental stage. No definitive analysis from the information developed to date is possible but the concept is worthy of further development. With further study it may be possible to define a broad statistical relationship between compaction, infiltration and acidification providing the opportunity for more informed decisions. Whether this method is used or another better method developed, the relationships need to be developed and understood. The optimum condition of the outer surfaces just below final cover is a key factor for desirable refuse site closing.
CHAPTER 10
MISCELLANEOUS RECOMMENDATIONS

This chapter briefly describes miscellaneous recommendations that may not have been covered elsewhere in the report.

Develop Additional Acid-Base Accounting (ABA) data for coal seam and immediate roof and floor strata: In many cases, current regulatory requirements are entirely sufficient to accurately characterize, predict, and control sulfate and chloride discharges. However, site-specific conditions may exist that make control of sulfate and chloride discharges problematic. In these situations, the following list identifies potential methods that can be used to assist the operator in reducing concentrations of sulfate and chloride discharges.

Additional geochemical characterization data can be developed on samples collected for existing requirements of geotechnical characterization (roof and floor stability) and should include total and pyritic sulfur content, chlorine, and neutralization potential (CCE). In order to calculate the ABA data (potential acidity, neutralization potential and net neutralization potential) for: 1) sink material from laboratory washability studies on cores, 2) immediate roof strata lithologies within 18-inches above the coal seam, and 3) immediate floor strata lithologies within 18-inches below the coal seam. Where multiple distinct lithologies exist within the immediate roof and floor strata, pyrite content and neutralization potential (CCE) data should be developed separately for each lithologic unit. If the mine undergoes significant expansion, additional ABA data analyses may be warranted. This can be obtained through core drilling samples or face channel samples that are taken under existing requirements of the operator.

The data above can provide valuable information on potential for sulfate and chloride generation potential that can be used for planning and design of management facilities, need for selective waste placement, critical period before acidification will start to occur during the oxidation and weathering process, alkaline amendment requirements, out-of-seam dilution, requirements for dilution and sedimentation ponds, etc.

Once the mine has been opened and processing plant is operational, mine operator can develop ABA data for different fractions of coarse refuse as well as composite coarse refuse, and FCPW or slurry to demonstrate the geochemical characteristics of this material as a result of actual processing activity. These data can be compared with similar data developed during pre-mining phase. These studies will provide predictive tools to the mine operator for future planning.

Once waste management operations are well established, characterization of the critical period can be used very productively in planning refuse disposal activities as well as size of active refuse disposal areas so that acidification can be minimized through controlled spreading of fresh reuse over weathered refuse. If site specific
conditions exist that lead an operator to believe that the critical period is different from the accepted time of 3-6 months, additional data collection may be warranted.

**Develop hydro-geologic and water quality data:** Mine operators provide hydro-geologic data and baseline groundwater quality data in the permit application. Generally this data is sufficient to accurately characterize and predict sulfate and chloride discharges from a mine site. However, site-specific conditions may call for additional data collection. For example: 1) are high chloride levels in groundwater being pumped from some Illinois mines have geologic origin such as upwelling, brine aquifer leakage and 2) are some chloride discharges related to historic oil production activity such as brine injection for secondary recovery?

**Minimize out-of-seam dilution:** One major way to minimize sulfate and chloride discharges is to minimize OSD. The operational cost of mining OSD and waste management, excluding the environmental costs associated with sulfate and chloride discharges varies $2.00 to $4.00 per clean ton. Operators should be encouraged to minimize OSD. Automated horizon control technologies should be developed and field demonstrated. Furthermore, efforts to manage coal processing waste underground should be encouraged.

**Develop economic processing technologies for dewatering of FCPW to eliminate slurry ponds:** This is an excellent area for research and development and should be pursued aggressively. Attempts to improve belt-press technology as well as paste thickener technology should be pursued aggressively to minimize long-term liability for mine operators. However, because current methods of slurry dewatering have proven to be inefficient at the operational level, the burden of research cannot be placed on the operators.

**Perform technical and economic feasibility studies for combined CCPW and FCPW disposal:** Based on literature review as well as limited testing during this study, there is definite potential that combined management can result in less long-term environmental problems from sulfate and chloride discharges point of view as well as reduce size of waste management facilities. Bench- and field-scale studies should be pursued to develop scientific data that includes both geochemical and geotechnical considerations. Similar to the previous technology, current co-disposal methods are not cost-effective and therefore, the burden of research cannot be placed on the operators.

**Develop improved technologies for evaluating field compaction:** As stated previously, current methods of measuring compaction with nuclear gauge devices are accurate and industry standard. However, it may be beneficial to develop simplified tools to assess field compaction in refuse disposal areas that provide potential for air and water percolation. Authors have developed a conceptual technique that appears to have potential. Consideration should be given to develop this or other concepts for industry use in lieu of nuclear moisture gage testing.
Consider use of biosolids: In a review of this report USEPA has suggested another promising CGMP that involves mixing biosolids with mined coal processing waste in discrete layers to minimize future AMD formation and sulfate discharges. Biosolids or organic solids (food waste, municipal solid waste, manures, etc.), when mixed with mine waste materials (that are devoid of organic carbon) produce exponential growth of sulfate reducing bacteria that shift the microbial food source from pyrite to waste carbon thus preventing AMD.

This was a project undertaken by the U. S. Bureau of Mines but remained incomplete because the Bureau was abolished. However, the project showed excellent results.
REFERENCES


Crislip, L. (2005) Personal Communication


USEPA (1995) Streams and Fisheries Impacted by Acid Mine Drainage in MD, PA, VA and WV, Wheeling. WV.


